Reliability Research of Vacuum Circuit Breaker Based on Degradation

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Abstract. As one of the terminal equipments of power system, circuit breaker plays the role of control, regulation and protection, and its reliability level has an important impact on the stability of power system. The key point of reliability research of circuit breaker is mechanical reliability. Aiming at the research of mechanical reliability of vacuum circuit breaker, in order to make full use of the process information of circuit breaker failure, this paper uses the method of reliability modeling based on degradation to do tens of thousands of degradation tests on six 12 KV permanent magnet vacuum circuit breakers, and uses the principal component analysis method to determine the degradation amount of overrun to establish the degradation process model. According to the over-range degradation data, Weibull distribution is used to establish the degradation distribution model, and the corresponding model parameters are calculated, and the reliability function and the reliability comparison curve are given.

1. Introduction

Circuit breaker is a switching equipment which can turn on, load and break the normal current of the operating circuit, and also can turn on, load and break the overload current (including short circuit current) within a specified time. As one of the terminal equipments of power system, circuit breaker plays the role of control, regulation and protection, and its reliability level has an important impact on the stability of power system. Circuit breaker life is divided into electrical life and mechanical life. Electrical life refers to the electrical performance of short-circuit interruption or split operation under rated current; mechanical life refers to the number of no-load operations that can be endured without repairing or replacing mechanical parts. Reference [1] shows that mechanical failure is the main cause of circuit breaker failure. The electric power department of our country has incomplete statistics on the failure rate of circuit breaker operation, and the mechanical failure accounts for more than 60%, many of which are also caused by mechanical reasons. Therefore, the emphasis of reliability research of circuit breaker is mechanical reliability.

Since the 1970s, scholars have carried out research on the reliability of circuit breakers. Reference [2-3] study the reliability of permanent magnet mechanism of VCB; In reference[4], A new research method is proposed for the medium-voltage vacuum circuit breaker’s mechanical condition monitoring, which combines the mechanism dynamic features simulation and mechanical condition recognition algorithm based on artificial neural networks; In reference[5], the reliability model of t circuit breaker subject to random shocks is established by the method of data statistics; Reference[6] establishes cascading Reliability Model for HV Circuit-Breakers. The influence of mechanical parameters of circuit breaker on its life is analyzed in reference [7], and the fault analysis of circuit breaker is combined. It is considered that the emphasis of research on circuit breakers should be shifted to the improvement of...
mechanical life and parameters; the reliability analysis of SF6 circuit breakers and operating mechanisms based on Bayesian statistics is introduced in reference [8]; the reliability estimation of SF6 circuit breakers is calculated by statistical method in reference [9], and the failure rate and residual life are given. In the published literature on the reliability of circuit breakers, consensus has been reached on the issue that the focus of the reliability of circuit breakers is mechanical reliability, but there are still some problems as follows: some literatures have analyzed the reliability of circuit breaker operating mechanism, but not the reliability of the whole machine; some literatures have qualitatively analyzed the reliability of the whole machine; The factors affecting the life of circuit breakers are not given the corresponding reliability model. In the fault analysis of circuit breakers, the failure data are processed directly by statistical analysis method, ignoring the failure process information of circuit breakers, which is not conducive to grasping the failure law of circuit breakers.

Aiming at the reliability research of vacuum circuit breakers, tens of thousands of degradation tests were carried out on six 12KV permanent magnet operated vacuum circuit breakers. The degradation process model was established by using principal component analysis method to determine the over-range as degradation quantity. According to the over-range degradation value, the normal distribution and Weibull distribution are used to establish the degradation distribution model, and the corresponding model parameters are calculated, and the reliability function and the reliability comparison curve are given.

2. Reliability research based on degradation

There are two methods for reliability modeling: Failure-based and degradation-based. Failure-based reliability modeling method refers to the method that establishes the distribution function of product failure and calculates product reliability according to the failure time or number. This method is suitable for life prediction technology in large sample situations. The degradation-based reliability modeling method pays attention to the information of product failure process and chooses the product life. The physical variables highly related to life and reliability (i.e. degradation quantity) are described by quantitative mathematical model, which describes the change rule with time and the failure process of products. Failure-based reliability modeling requires the use of statistical methods to process failure time data, which is inappropriate in the absence of sufficient failure samples. Circuit breaker, a small sample product with long life and high reliability, is more suitable for reliability research method based on degradation [10-11].

Assuming that the distribution form of performance degradation of the same kind of product samples is the same at different measurement time, the distribution parameters change with time, that is to say, the degradation of product performance at different measurement time obeys a unified distribution family, whose parameters are functions of time variables. The difference of product performance degradation quantity distribution is related to time. After analyzing the variation rule of degradation quantity distribution parameter with time, the reliability of product can be evaluated by reliability evaluation method.

In reliability analysis and life test, the commonly used models are exponential distribution, normal distribution, lognormal distribution and Weibull distribution. Among them, Weibull distribution has strong adaptability to various types of test data, and the range of shape parameters reflects the failure characteristics of products, so it is most widely used in reliability engineering. Weibull distribution is based on the life data of failure mode to study the relationship between the life time of components and its reliability. Because of its shape parameters, Weibull model can fit the model flexibly. When the failure analysis object is small sample data, Weibull distribution has better superiority than other distributions. When the test data is sufficient, it can even be used without failure. Therefore, Weibull distribution can be widely used in various fields: reliability and failure analysis of electronic products; industrial manufacturing; weather prediction; radar system; repeated claims of quantitative life insurance model; wind speed, etc.
If the performance degradation quantity $y$ obeys Weibull distribution with shape parameter $m_y(t)$ and scale parameter $\eta_y(t)$, then when the product is failure criterion $y \leq D_f$, the relationship between reliability and performance degradation distribution is as follows.

$$R(t) = 1 - P(y \leq D_f) = \exp \left\{ -\frac{D_f}{\eta_y(t)}^{m_y(t)} \right\}$$

(1)

Scale parameters and shape parameters are taken as functions of time, and are modeled and solved.

3. Reliability on reliability of vacuum circuit breaker

According to the national standard GB3309, the mechanical life of vacuum circuit breaker is that the circuit breaker can reliably complete the required closing and opening operations in accordance with the instructions; when the performance parameters of the circuit breaker are obviously deteriorated or the key components are deformed, the basic operation and function of the equipment can’t be completed, the circuit breaker is considered to be invalid.

According to GB/T 5080 series standards, six prototypes of 12 kV permanent magnet operated vacuum circuit breaker have been selected as the research object, and the whole set of prototypes has been numbered. At room temperature, the mechanical characteristics of the main circuit are measured without voltage and current, and the initial mechanical characteristics are taken as the reference parameters. The mechanical characteristic parameters in the test were obtained when the test sample was operated in C-15-O-15 seconds sequence under the rated power supply voltage of 220V AC. After every 1000 mechanical operations, the mechanical characteristic parameters of the prototype are recorded without dismantling any parts of the circuit breaker.

The function of over-range is to ensure that the contact can maintain a certain contact pressure and reliable electrical contact after a certain degree of electrical wear. In the opening process, the dynamic contacts can obtain a certain initial impact kinetic energy, increase the initial acceleration of the dynamic contacts and break the melting joint of the contacts, so that the vacuum circuit breaker can be smoothly cushioned by the spring force of the contacts in the closing process, and reduce the impact force.

| Tab.1 Vacuum circuit breaker overtravel data |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $t$/1000    | 1#          | 2#          | 3#          | 4#          | 5#          | 6#          |
| 0           | 3.82        | 3.43        | 3.76        | 3.53        | 3.32        | 3.42        |
| 1000        | 3.80        | 3.39        | 3.73        | 3.52        | 3.31        | 3.40        |
| 2000        | 3.73        | 3.38        | 3.71        | 3.51        | 3.30        | 3.39        |
| 3000        | 3.69        | 3.32        | 3.69        | 3.49        | 3.29        | 3.35        |
| 4000        | 3.66        | 3.27        | 3.68        | 3.48        | 3.27        | 3.32        |
| 5000        | 3.65        | 3.25        | 3.66        | 3.46        | 3.25        | 3.30        |
| 6000        | 3.63        | 3.22        | 3.63        | 3.43        | 3.23        | 3.27        |
| 7000        | 3.57        | 3.15        | 3.60        | 3.41        | 3.20        | 3.26        |
| 8000        | 3.51        | 3.10        | 3.59        | 3.40        | 3.18        | 3.24        |
| 9000        | 3.51        | 3.09        | 3.55        | 3.29        | 3.16        | 3.23        |
| 10000       | 3.50        | 3.08        | 3.54        | 3.38        | 3.13        | 3.22        |
| 11000       | 3.48        | 3.06        | 3.52        | 3.37        | 3.11        | 3.20        |

According to the product performance degradation quantity obtained in Table 1, the Weibull probability map is obtained by Weibull transformation. The degradation quantity at each time is judged to conform to Weibull distribution by graph method. The shape and scale parameters at each measuring time are determined by maximum likelihood method, as shown in Table 2.
Tab. 2 Estimation of overtravel Weibull distribution parameters

| t/（次） | Shape parameter | Scale parameter |
|--------|----------------|----------------|
| 0      | 3.8109         | 20.0384        |
| 1000   | 3.7875         | 19.5208        |
| 2000   | 3.6796         | 18.0991        |
| 3000   | 3.6693         | 18.8023        |
| 4000   | 3.6202         | 20.0956        |
| 5000   | 3.6162         | 17.6805        |
| 6000   | 3.4309         | 19.1792        |
| 7000   | 3.4257         | 17.7743        |
| 8000   | 3.4223         | 18.1599        |
| 9000   | 3.4175         | 21.2517        |
| 10000  | 3.3836         | 20.4214        |
| 11000  | 3.3768         | 18.6367        |

Among them, the shape parameters of samples are approximate linear functions of time, and the scale parameters do not change much with time, so the estimates of shape parameters and scale parameters can be obtained.

\[
\hat{\eta}_i(t) = -0.0428t + 3.832
\]

\[
\hat{m}_i(t) = \frac{1}{t^{12}} \sum_{i=1}^{12} \hat{m}_i(t) = 18.305
\]

By substituting sum formula (1) and taking failure threshold as \( D_f = 4 \) mm, the reliability function of the product at a given time \( t \) is obtained when the deterioration of product performance obeys Weibull distribution. The reliability curve of the product at a given time \( t \) is shown in Figure 1.

\[
R(t) = \exp\left[-\left(\frac{4}{-0.0428t + 3.832}\right)^{18.305}\right]
\]

Fig. 1 Reliability curve of vacuum circuit breaker

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References
[1] Janssen, A., Makareinis, D., & Sölver, C. E. (2013). International surveys on circuit-breaker reliability data for substation and system studies. IEEE Transactions on Power Delivery, 29(2), 808-814.
[2] Wang, Y., Liu, Y., Mu, Y., Zhao, X., Huang, Z., & Zou, J. (2015, October). Reliability assessment of permanent magnetic actuator for vacuum circuit breaker. In 2015 3rd International Conference on Electric Power Equipment–Switching Technology (ICEPE-ST) (pp. 553-556).
IEEE.

[3] Li, H., Sun, L., Yao, X., Geng, Y., Liu, Z., & Wang, J. (2015, October). Research on mechanical reliability of a permanent magnetic actuator for a 126kV vacuum circuit breaker. In 2015 3rd International Conference on Electric Power Equipment–Switching Technology (ICEPE-ST) (pp. 570-573). IEEE.

[4] Rong, M., Wang, X., Yang, W., & Jia, S. (2005). Mechanical condition recognition of medium-voltage vacuum circuit breaker based on mechanism dynamic features simulation and ANN. IEEE Transactions on Power Delivery, 20(3), 1904-1909.

[5] Medjoudj, R., Medjoudj, R., & Aïssani, D. (2011). Reliability modelling and data analysis of vacuum circuit breaker subject to random shocks. International Journal of Science, Engineering and Technology, WASET, 649-653.

[6] Choonhapran, P., & Balzer, G. (2007, July). Cascading reliability model for hv circuit-breakers. In 2007 IEEE Lausanne Power Tech (pp. 1770-1775). IEEE.

[7] Ebeling, C. E. (2004). An introduction to reliability and maintainability engineering. Tata McGraw-Hill Education.

[8] Muratović, M., Sokolić, K., & Kapetanović, M. (2013, November). Modelling of high voltage SF6 circuit breaker reliability based on Bayesian statistics. In 2013 7th IEEE GCC Conference and Exhibition (GCC) (pp. 303-308). IEEE.

[9] Xiang Zhang, Ernst Gockenbach, Zhaolin Liu, et al. Reliability estimation of high voltage SF 6 circuit breakers by statistical analysis on the basis of the field data[J]. Electric Power Systems Research, 2013, 103:105-113.

[10] Elsayed, E. A. (2012). Overview of reliability testing. IEEE Transactions on Reliability, 61(2), 282-291.

[11] Si, X. S., Wang, W., Hu, C. H., & Zhou, D. H. (2011). Remaining useful life estimation—a review on the statistical data driven approaches. European journal of operational research, 213(1), 1-14.