Robustness Assessment of Life-Cycle-Management of CV Cables based on Degradation Diagnosis

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Abstract: Life-cycle management based on the degradation diagnosis is useful for preventing an unexpected failure and extending service life of electric power apparatuses, minimizing life-cycle cost. In our previous study, we formulated a numerical model of life-cycle management based on time-based maintenance and condition-based maintenance. Then, we applied the model for evaluating the economic effect of degradation diagnosis of power cables, assuming that the maximum length of water tree as a replacement criterion can be measured nondestructively. To carry out reliable life cycle management, however, accurate data on the relation between extent of degradation and failure probability or remaining life are necessary. In this study, we examine the influence of accuracy of the data used to determine the optimum diagnostic parameters and evaluate how the life-cycle cost is affected by the employment of inaccurate data. The results show that the condition-based maintenance with degradation diagnosis can be less subject to the accuracy of the back data and is possible to realize the reliable life-cycle management.

INTRODUCTION

Due to the competitive deregulation of electric power industry, further cost reduction is required for the power system operation without lowering the high reliability, and it is desirable to prolong the service time of power apparatuses as long as possible. The life-cycle management (LCM) based on the degradation diagnosis is useful for preventing an unexpected failure and extending service life of electric power apparatuses, resulting in the decreased life-cycle cost (LCC). The setting of adequate conditions, such as the periods of diagnosis and replacement of aged equipment, is important for minimizing LCC of the equipment operation taking diagnosis costs into account. In our previous study, therefore, we formulated a numerical model of life-cycle management based on condition-based maintenance (CBM) [1, 2]. Then, assuming that the maximum length of water tree as a replacement criterion can be measured nondestructively, we evaluated the economic effect of degradation diagnosis of power cables with water tree degradation as an example of power apparatuses, for which relatively rich data on degradation and remaining life are available. For comparison, we also formulated a numerical model of life-cycle management based on time-based maintenance (TBM), where all power cables are replaced with a certain interval even though some can be still usable. Then, we demonstrated that CBM by degradation diagnosis can contribute to realize more cost-effective life-cycle management compared with TBM.

To carry out reliable life cycle management, accurate data are necessary as well as a well-established diagnostic method. However, power apparatuses are used under various conditions and furthermore failure probability would be different even and the same condition. Therefore, the data available for LCM are limited and it is important to carry out robust LCM based on the insufficient and/or inaccurate data. In this paper, we examine the influence of accuracy of the data on the LCM based on the degradation diagnosis and evaluate its reliability and robustness.

NUMERICAL MODEL OF LIFE-CYCLE MANAGEMENT

In our previous study, we formulated a numerical model of life-cycle management based on CBM, assuming that the maximum length of water tree as a replacement criterion can be measured nondestructively. In this study, we take into account two management methods with degradation diagnosis, i.e. CBM-1 and CBM-2. In CBM-1, as the diagnosis parameters, i.e. the diagnosis interval T and replacement criterion l_c are unchanged throughout the service life of a power cable. For representing more condition-oriented life-cycle management, CBM-2 has two diagnosis intervals. In CBM-2, the first diagnosis is carried out T_1 years after the installation, and the later diagnosis is carried out with the interval of T_2 years. For comparison, the results are discussed together with the results of life-cycle management based on TBM, where all power cables are replaced with a certain fixed interval.

The calculation of life-cycle cost (LCC) for CBM-1, CBM-2 or TBM is carried out with the following steps.

Step-1: Data processing
Step-2: Calculation of failure probability $P(k)$ and replacement rate $R(k)$ in the k-th year
Step-3: Calculation of LCC for various diagnosis conditions

Data Processing

The accelerating-degradation data of practical 6.6 kV XLPE cables were used as shown in Figures 1 and 2 [3]. The samples were cut from the cables that had been

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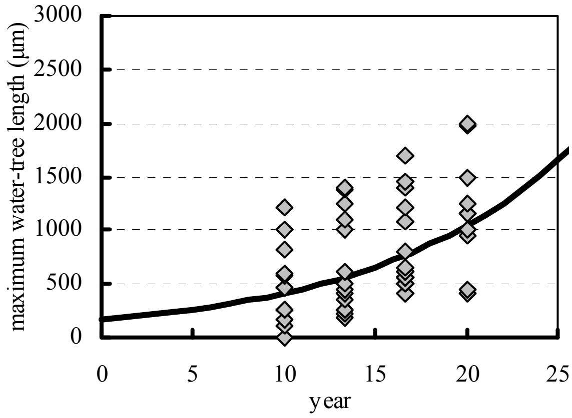

Figure 1 Relation between operation period and maximum water-tree length of CV cable.

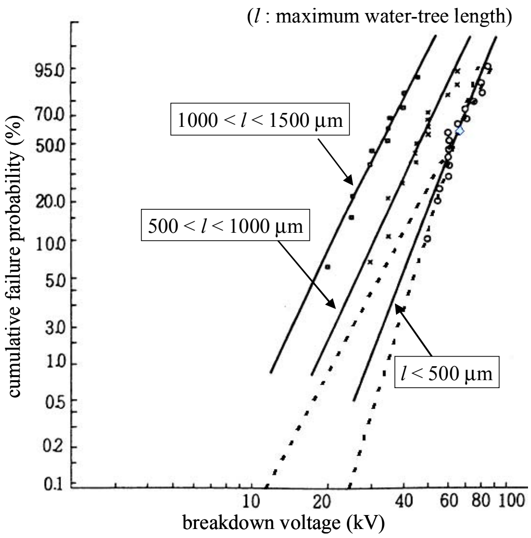

Figure 2: Weibull distribution plot of breakdown voltage for cables with different maximum water-tree length.

used for 10 years. The length of each sample was 5 m. The test was carried out at a frequency of 1 kHz, and the corresponding practical degradation time at 50 Hz is taken to be 20 times as long as the test period.

The annual density distribution of maximum water tree length l in the k-th year $N_k(l)$ was expressed as the following logarithmic normal distribution.

$$N_k(l) = \frac{1}{\sqrt{2\pi\sigma(k)^2}} \frac{1}{l} \exp\left[-\frac{(\ln l - \mu(k))^2}{2\sigma(k)^2} \right] \quad (1)$$

$$\mu(k) = 0.092k + 5.11 \quad (2)$$

$$\sigma(k) = 0.617 \quad (3)$$

From the Weibull distribution plot of breakdown voltage for the cables with different maximum water tree length shown in Figure 2, we formulated the correlation between maximum water tree length l [μm] and failure probability of the cable $f(l)$ at the maximum system voltage 4.0 kV which is equal to 1.05 times of the rated phase voltage.

$$f(l) = 3.196 \times 10^{-14} \times l^{3.649} \quad (4)$$

In this study, $N_k(l)$ and $f(l)$ are called as master data, and assumed to be accurate.

Failure Probability and Replacement Rate

The diagnosis is carried out periodically, in which the maximum water tree length is assumed to be measured nondestructively. The criterion for cable replacement is defined as a critical water tree length l_C [μm]. If the diagnosis is carried out at the beginning of the k-th year, only the cables with water tree length less than l_C are left just after the diagnosis. The cables with water tree length larger than l_C as well as the cables reaching their estimated lifetime (50 years in this study) are replaced with new ones, keeping the total number of cables constant throughout the management period.

The number of cable failure in the k-th year is expressed as follows.

$$p(k) = \int_0^{l_C} N_k(l) \cdot f(l) \cdot dl \quad (5)$$

The number of cables in the k-th year, in which the diagnosis is not carried out, is also formulated, considering the failure probability of cables with water tree length larger than l_C. The failure probability in the k-th year is expressed as the ratio of the total failure number to the total number of cables at the beginning of the k-th year.

Details for calculating the failure probability $P(k)$ and the replacement rate $R(k)$ in the k-th are described in refs. [1, 2].

Calculation of Life-cycle Cost for Various Diagnosis Conditions

As for the typical cables, the number of remaining cables which have been in use for k years in the n-th calculation year $g_n(k)$ is calculated by considering $P(k)$ and $R(k)$ [1, 2]. Assuming failure loss cost C_f, replacement cost C_r and diagnosis cost C_d expressed as relative values, the total life-cycle cost LCC is expressed as follows.

$$LCC = TC_f + TC_r + TC_d \quad (6)$$

$$TC_f = \sum_{n=1}^{n_{max}} \left[C_f \cdot \sum_{k=1}^{k_{max}} g_{n-1}(k-1) \cdot \{1 - R(k-1)\} \cdot P(k-1) \right] \quad (7)$$

$$TC_r = \sum_{n=0}^{n_{max}} [C_r \cdot g_n(0)] \quad (8)$$

$$TC_d = \sum_{n=2}^{n_{max}} \left[C_d \cdot \sum_{k=2}^{k_{max}} g_{n-1}(k-1) \right] \quad (9)$$

In the following study, the LCC are shown for the case of C_f=10, C_r=1, C_d=0.001. Because the annual cost fluctuates in a period which is equal to the replacement time, the calculation period is chosen to be long enough, i.e. 300 years, so that the total cost with different replacement times can be compared.

LIFE-CYCLE COST BASED ON APPROPRIATE MASTER DATA

As a base case, we examine the optimal diagnosis parameters in CBM-1 and CBM-2, and the optimal replacement interval in TBM. Figure 3 shows the relation between the replacement interval and LCC in TBM. Hereinafter, LCC is normalized by the minimum value of LCC in TBM. Figure 3 also shows the relation between the diagnosis interval and LCC in CBM-1, where the replacement criterion of CBM-1 is chosen as optimal value to minimize LCC.
The LCC of T BM becomes very high if the replacement is not carried out with appropriate interval. This indicates TBM based on inaccurate data leads to very high LCC.
On the other hand in CBM-1, LCC is smaller than that of the optimum TBM for various values of diagnosis interval. Figure 4 shows the relation between diagnostic condition and LCC in CBM-1. LCC of CBM-1 can be lower than that of TBM for various values of replacement criterion ranging 1500 – 2500 μm as well as diagnosis interval.
Figure 5 shows the relation between replacement criterion and LCC in CBM-1 and CBM-2. The advantage of CBM-2 against CBM-1 appears if the replacement criterion can be set smaller, i.e. shorter length for maximum water tree length. The results suggest that the condition-based management can contribute to a reliable and robust life-cycle management even if the diagnosis parameters can not be set at the optimum value.

LIFE-CYCLE COST BASED ON INACCURATE DATA

In many cases, data available are not sufficient for precise LCM and LCM has to be carried out based on in accurate data. In this paper, we examine the influence of accuracy of the data on the LCM based on degradation diagnosis and evaluate its reliability and robustness with the following procedures.

Evaluation Procedure

First, by using the data which is intentionally formulated to be different from the master data, we determine the apparent optimal diagnosis parameters. Because the master data represents the actual failure probability of cables appropriately, the LCC calculated by using the apparent optimal parameters is higher than the cost using the master data. However, if the increase in LCC calculated with the apparent optimal parameters is small, we can regard the life-cycle management method as reliable and robust, even if the actual failure probability of cables concerned is slightly deviates from the master data.

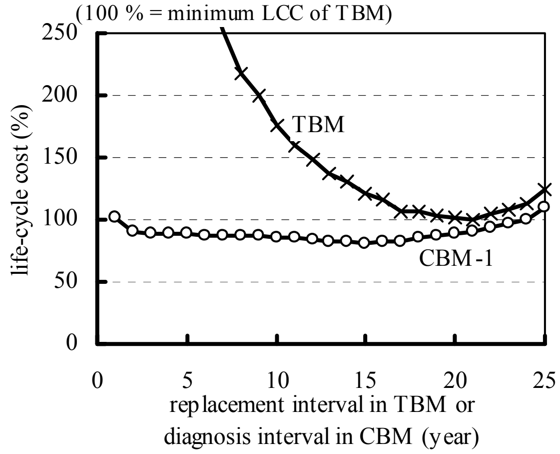

Figure 3: Relation between replacement or diagnosis interval and LCC in TBM and CBM-1

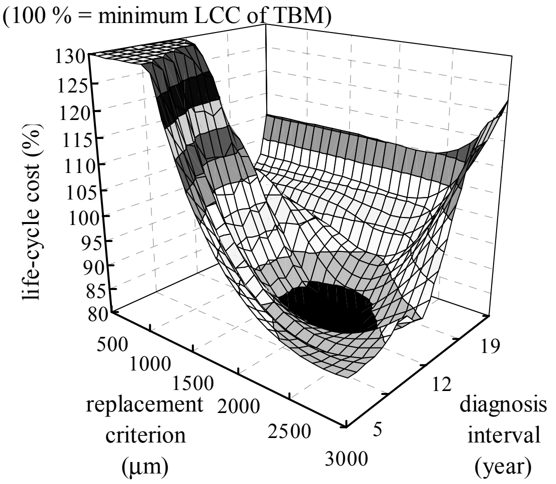

Figure 4: Relation between diagnostic condition and LCC in CBM-1.

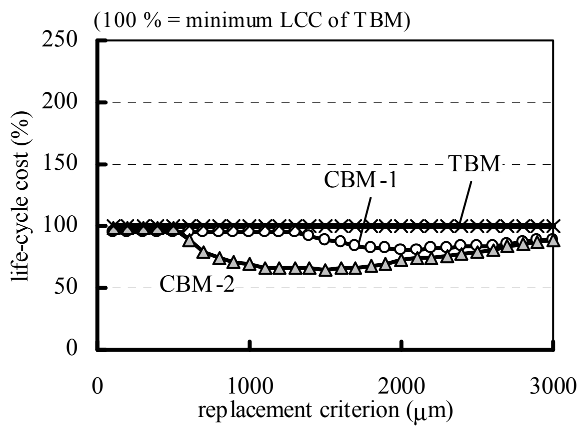

Figure 5: Relation between replacement criterion and LCC in CBM-1 and CBM-2

Inaccurate Data Regarding Standard Deviation of Annual Change in Maximum Water tree length

Assuming that the standard deviation of annual change in maximum water tree length is larger than the actual one , we calculated the increase in LCC. Figure 6 shows the results. In this case, because we expect a larger number of CV cables with longer maximum water tree length, and hence possible higher failure loss in the future, the replacement interval in TBM is set shorter than in the optimum value, increasing the cable replacement cost. In CBM-1, although we expect larger number of CV cables with longer maximum water tree length and set shorter diagnosis interval, the number of cables actually replaced is much smaller due to the diagnosis, resulting in smaller increase in LCC in CBM-1 than in TBM. In CBM-2, the first diagnosis is in the second year after cable installation, and the cables with maximum water tree length of a few hundred μm are replaced. The second diagnosis is scheduled after about 25 years regardless of the evaluated standard deviation assumed this work. Therefore, LCC in CBM-2 is almost independent of the assumed standard deviation.

Inaccurate Data Regarding Weibull Distribution Plot of Breakdown Voltage

Assuming that the shape parameter of Weibull distribution plot is different value from the actual value as shown with dotted line in Figure 2, we calculated the increase in LCC. Figure 7 shows the results. When we use the smaller shape parameter, we expect smaller change in failure probability with the increase in maximum water tree length. Therefore, in TBM, longer replacement interval is chosen. This increases the failure loss cost with large failure probability and results in higher LCC. In CBM-1 and CBM-2, however, the increase in LCC is small due to diagnosis.

CONCLUSION

LCC was calculated in TBM and CBM. If we use the inaccurate data for TBM, the LCC becomes very large. On the other hand in CBM, the LCC is lower than that of the optimum TBM, and does not change so much for the replacement criterion. The results suggest that CBM can contribute to a reliable and robust life-cycle management even if the diagnosis parameters can not be set at the optimum value.

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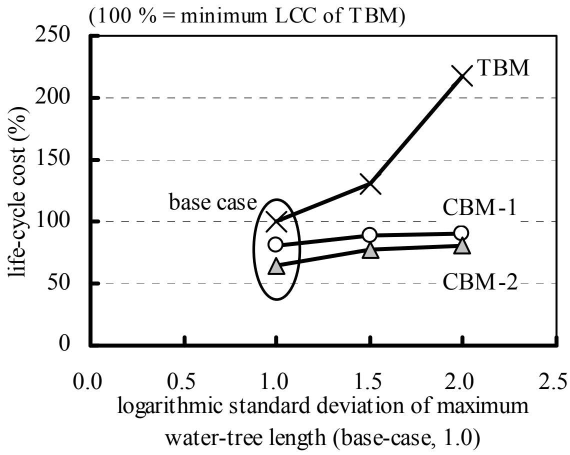

Figure 6: Increase in LCC by using improper master data regarding standard deviation of annual change in maximum water tree length of CV cable.

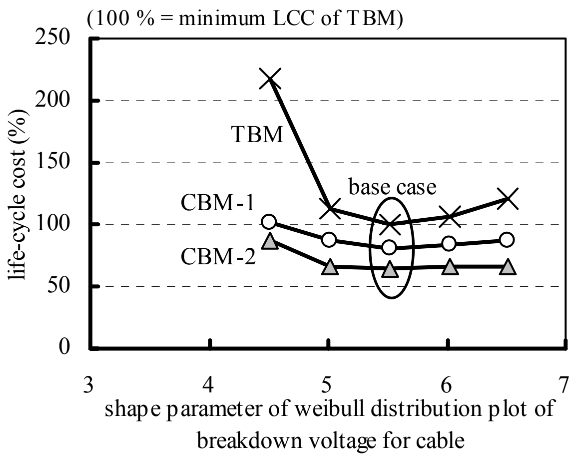

Figure 7: Increase of LCC by wrong assumption of shape parameter of weibull distribution plot of breakdown voltage.