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Lifetime Assessment Method using Multiple-Stress Acceleration Aging for Flexible Cable of Portable Electric Machines

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Abstract – In this study, in order to analyze the lifetime for flexible cables used in portable electric machines, artificial accelerating aging was carried out for VCT(Vinyl Cab-Tire) cables in consideration of thermal, mechanical and electrical multiple-stresses. Accelerated aging factors were calculated with aging temperatures based on the Arrhenius relationship. Through Weibull statistical analysis in the AC breakdown voltages for aged cables after low-temperature mechanical tests, it was analyzed that AC breakdown voltages were proportional to the elongation rates and 19kV of the scale parameter in Weibull analysis was suggested as limit value of lifetime. Using this criterion, it was deduced that the lifetimes with thermal and mechanical multiple-stresses for 70℃, 50℃ and 40℃ continuous operation were calculated to be 3.3 years, 9.9 years and 15.7 years respectively. Based on these analysis procedure, it is possible to suggest the lifetime assessment technique with multiple-stresses for low voltage cables.

Keywords: Lifetime, Low voltage flexible cable, Thermal and mechanical stresses, AC breakdown

1. Introduction

For portable electric machines used for the construction site, the main cause of electric shock accidents would be insulation damages of cables [1], which results from the loss of insulation performance and carelessness of management supervision. In particular, cables in potable facilities such as electric motors, welding machines, temporary electric supplies etc. are always faced with mechanical damages and degradation in insulation layers due to problems in various construction work types and methods and harsh working environment. But, research on insulation degradation and lifetime assessment for low-voltage cables has not been established enough compared with high voltage cables. [2,3]

VCT(Vinyl Cab-Tire) cables are widely used in portable electric machines in the construction site because of flexibility and cheapness of PVC insulation and sheath. In comparison with PNCT(EPR insulation Chloroprene sheath Cab-Tire) cables and WCT(Rubber insulation Rubber sheath Cab-Tire) cables, there would be high probability of electric shocks and fire accidents caused by damage of insulating layer and sheath in case of VCT cables owing to decreased flexibility for long period usage or severe mechanical impacts. [4,5] However, the life assessment and the replacement cycle according to degradation for VCT cables have never been reported.

Therefore, in this study, the lifetime characteristics of VCT cables were focused on. The degradation evaluation and the lifetime assessment for the thermally aged cables were carried out through mechanical stresses and electrical breakdown experiments for the VCT cables.

2. Experimental Methods

2.1 Thermal degradation method

In general, thermal degradation for the polymer insulation material is known to be followed with Arrhenius relationship equation. [6] Thus, before starting the thermal aging process in this study, it is possible to estimate lifetime roughly and to decide accelerated aging temperatures. In the preliminary experiment at 150℃, it was found out that PVC insulation was rapidly degraded. Therefore, aging temperatures of 110℃, 130℃ and 140℃ were selected in considering to ensure proper degradation mechanism.

Thermal accelerated aging method was adopted in reference to KS C IEC 60811-1-2, 8. 'Method of thermal aging'. [7] Specimens were installed vertically inside an oven as the state of the products including conductor, insulation and sheath. Each specimen was placed each other over 20mm in consideration of air circulation.

2.2 Method for mechanical stress application

The mechanical degradation during the use of VCT cables is generally considered as trampled, pressed, bent and so on. However, it was not possible to simulate the mechanical degradation with regard to the lifetime quantitatively. Therefore, in this study two methods were

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adopted for the lifetime evaluation using the biggest mechanical stress in the KS C IEC 60502-1 and KS C IEC 60811-1 standard.

2.2.1 Low-temperature impact test

After cooling the specimen as a finished product during more than 16 hours at low-temperature of –15℃, the hammer of 500g was dropped from 100mm height. Damage by the impact was investigated with bare eyes.

2.2.2 Low-temperature bending test

After cooling the specimen as a state of an insulation with conductor or a finished product during more than 16 hours at low-temperature of –15℃, wind the specimen to a cylinder which has a diameter of 4~5 times specimen diameter up to maximum 10 times with a speed of 1 cycle per second. Damage by the bending was investigated with bare eyes.

2.3 Electrical breakdown method

Insulation breakdown voltage was measured with submergence test according to KS IEC 60811-1 standard. After extracting conductor strands including insulator among the VCT cables having thermal degradation and mechanical stress, AC voltage was applied to the conductor of the specimen immersed with water.

AC voltage was raised up with the speed of approximately 0.1 kV per second until the insulation breakdown occurred. After experiment for at least 10 specimens per each degradation condition, scale parameters were obtained by using Weibull statistics.

2.4 Elongation rates measurement

The measurement of elongation rates was carried out for tubular insulation specimens removing completely conductor and sheath after thermal accelerated aging. A specimen with length of 80 mm to the tensile strength tester was installed and tested. The elongation rate was calculated with the elongated length until the sample had broken in gauge of 20mm section. The median value of three or more specimens except the maximum and minimum value among at least five specific data was obtained as representative value.

After measuring the elongation rate of the aged specimens, the minimum limit less than 150% elongation rate in the VCT cables according to KS C IEC 60502-1 standard was adopted as the life assessment guideline. Using this limit, expected lifetimes were calculated for various temperatures. The elongation rate $\epsilon_t\ (t)$ is defined with the following equation.[8]

$$\epsilon_t\ (t) = \frac{\text{Extended length} - \text{Gauge length}}{\text{Gauge length}} \times 100\% \qquad (1)$$

3. Lifetime Analysis using Elongation Rates for the Thermal Degradation

The molecular weight is generally decreased in polymer materials during thermal degradation, because chains of molecules are broken, which leads to the reduction of physical characteristics such as elongation rate and tensile strength. It is known that tensile strength in polymeric materials decreases exponentially with time at constant temperature. [9]

$$\epsilon_t\ (t) = \epsilon_{t_0}\ e^{-B_{\epsilon_t}(T)t} \qquad (2)$$

Here, $\epsilon_t\ (t)$ is the elongation rate in time *t*. And, ϵ_{t_0} is the initial elongation rate, $B_{\epsilon_t}(t)$ is a coefficient of degradation condition and temperature, and it is assumed to follow the Arrhenius equation as follows;

$$B_{\epsilon_t}(T) = Be^{\frac{E_a}{RT}} \qquad (3)$$

Here, E_a is activation energy and approximately 92.16 [kJ/mol] in the case of PVC insulation of cables. [10] T is the temperature [K] of the specimen, R is the gas constant (8.314 [J/mol]), and B is the environmental factor $[h^{-1}]$ which give an effect on the degradation of the specimen such as water, oxygen, acid, etc.

Fig. 1 shows the change of elongation rate with aging time for various aging temperatures. Elongation rates are reduced exponentially with time and more severely with the aging temperature from same initial value.

The lifetime of the VCT cables can be obtained using data of elongation rates as shown in Fig. 1 as follows;

1) Derive trend formula and degradation coefficient $B_{\epsilon_t}(T)$ with aging temperature

$$\begin{aligned} \epsilon_t(t)_{110℃} &= 219.9e^{-0.001846t} \\ \epsilon_t(t)_{130℃} &= 219.9e^{-0.011087t} \\ \epsilon_t(t)_{140℃} &= 219.9e^{-0.022404t} \end{aligned} \qquad (4)$$

2) Calculate Arrhenius relationship coefficient E_a/RT and environmental factor B with aging temperature

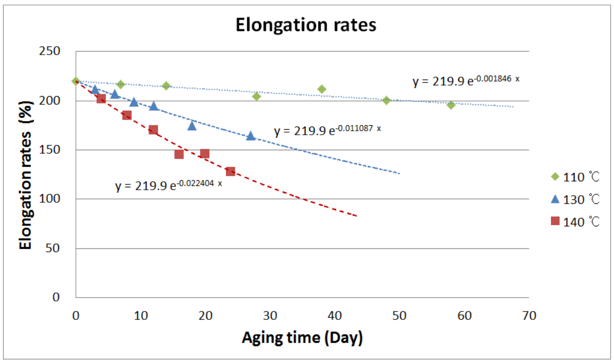

Fig. 1. Elongation rates with the thermal degradation

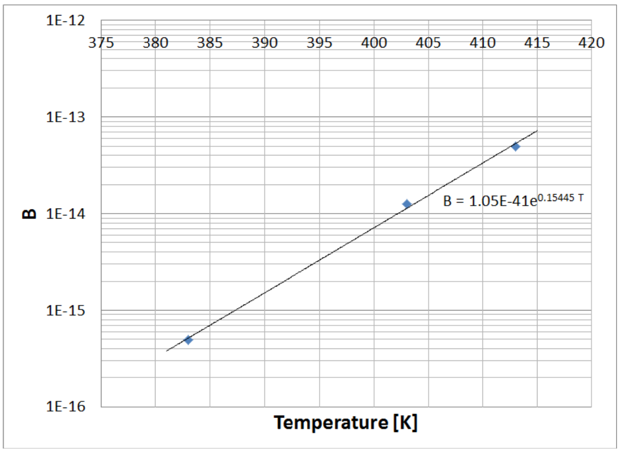

Fig. 2. Trend formula for environmental factor *B*

Table 1. Calculations for accelerated aging factors and lifetime limits in equivalent operating years

T [°C]	$\frac{E_a}{RT}$	$B_{\epsilon_t}(T)$	B	Accel. aging factors	Lifetime limit in equivalent operating years
140	4.53×10^{11}	0.022404	4.94×10^{-14}	193.9	17.1 days
130	8.82×10^{11}	0.011087	1.26×10^{-14}	96.0	34.5 days
110	3.71×10^{12}	0.001846	4.97×10^{-16}	16.0	207.2 days
70	1.08×10^{14}	0.0001155	1.06×10^{-18}	1.0	9.1 years
50	8.02×10^{14}	0.0000398	4.85×10^{-20}	0.337	26.9 years
40	2.40×10^{15}	0.0000249	1.04×10^{-20}	0.215	42.1 years

3) Derive trend formula for environmental factor *B* as shown in Fig. 2

$$B = 1.05\times 10^{-41}\cdot e^{0.154457T} \tag{5}$$

4) Calculate B and complete the lifetime formula at 70℃ of maximum permissible temperature in VCT cables

$$\epsilon_t(t)_{70℃} = 219.9e^{-0.000116t} \tag{6}$$

On the other hand, in the case of PVC materials according to the KS C IEC 60502-1, the elongation rate of 150% should be regarded as disqualification. Thus, this value can be considered as the criterion of lifetime limit. In other words, it is able to consider the lifetime limit at the point of less than the elongation rate of 150% by long-term degradation in use. Using this relationship eventually, calculations for accelerated aging factors and lifetimes in equivalent operating years could be made as shown in Table 1. The lifetime in equivalent operating years at 70℃ was calculated with approximately 9.1 years.

This result is generally quite low compared with as-considered lifetime of 20~30 years for VCT cables. The reason of this difference is due to the calculation under assumption of continuous operation at 70℃. If the operation temperature of cables was considered as the actual case, it is expected to take longer lifetime than this value. When considering the lower continuous operation temperature of cables, lifetimes can be obtained 26.9 years at 50℃ and 42.1 years at 40℃.

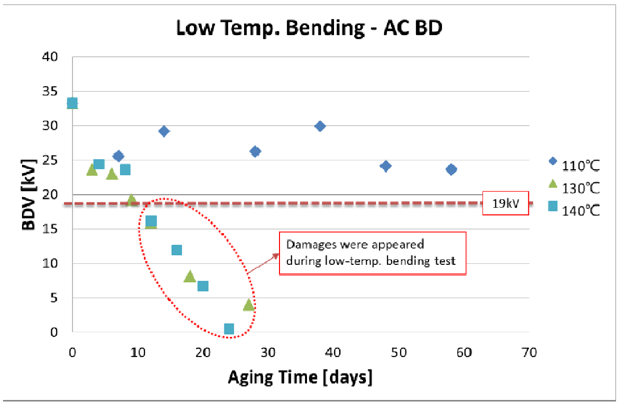

Fig. 3. AC breakdown voltage after low-temperature bending test with aging time

$$\begin{aligned}\epsilon_t(t)_{50℃} &= 219.9e^{-0.0000389t}\\ \epsilon_t(t)_{40℃} &= 219.9e^{-0.0000249t}\end{aligned} \tag{7}$$

4. Analysis of AC Breakdown for Specimens with Thermal and Mechanical Multiple-stresses

4.1 AC breakdown voltage after low-temperature bending test

Fig. 3 shows the result of AC breakdown experiments for thermally aged specimens after low-temperature bending test. In case of 110℃ degradation, AC breakdown voltages were slightly decreased with aging time, but they showed more than 5kV and no physical damage occurred up to 58 days. But in the case of the degradation of 130℃ and 140℃, damaged specimens in insulation began to appear during the low-temperature bending test after more than 10 days aging. In the submergence AC breakdown test, the damaged specimen during low temperature bending test showed 0kV, because AC voltage could not be applied to the damaged specimen. Due to these damaged specimens for severe aging conditions, the AC breakdown voltage as the scale parameter of Weibull statistics showed less than 19kV. Therefore, breakdown voltage of 19kV was considered as the lifetime limit through AC breakdown test of the specimen with thermal and mechanical multiple-stresses. In between 130℃ and 140℃ degradation, there was no significant difference in AC breakdown voltage, which implies that mechanical damages were similar over a certain level of degradation.

4.2 AC breakdown voltage after low-temperature impact test

Fig. 4 shows the result of AC breakdown experiment for

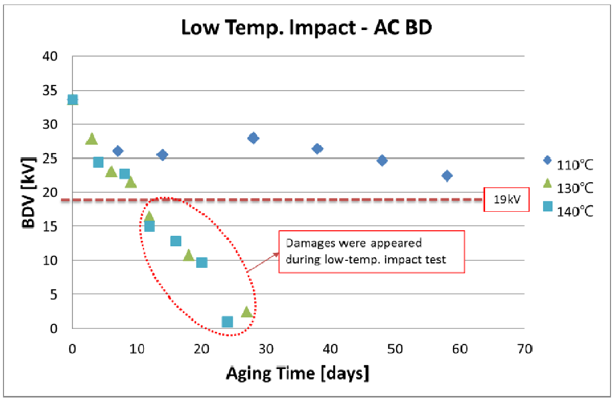

Fig. 4. AC breakdown voltage after low-temperature impact test with aging time

thermally aged specimens after low-temperature impact test. The result was almost the same as that of low-temperature bending test. In the low-temperature impact test, less than 19kV of the scale parameter in Weibull statistics could be also considered as the lifetime limit, because mechanical damages occurred in the low-temperature impact test for the specimens with the aging condition showing less than 19kV breakdown voltage value.

Thus, considered with above results, the mechanical stress in low-temperature bending test and low-temperature impact test could be regarded to be similar, which leads to the similar lifetime limit obtained from two experiments.

5. Lifetime Assessment for VCT Cables

5.1 Correlation between AC breakdown voltages and elongation rates

Fig. 5 shows the correlation between AC breakdown voltages after low-temperature bending test and elongation rates for the degraded specimens. Elongation rates and AC breakdown values were shown to be approximately proportional, which means that the reduction in physical properties leads to the reduction of dielectric strength. In Fig. 5, the shaded area above breakdown voltage of 19kV and elongation rate of 150% can be considered as an area of lifetime limit.

Similar with Fig. 5, Fig. 6 shows the correlation between AC breakdown voltage after testing low-temperature impact test and elongation rates. Since AC breakdown voltages after the low-temperature bending test and the impact test showed very close similarity to each other, elongation rates and AC breakdown voltages were generally shown to be proportional. Also, the shaded area above 19kV of AC breakdown voltage and 150% of elongation rates in Fig. 6 shows the same as those in Fig. 5, which seems to be considered as an area of lifetime limit.

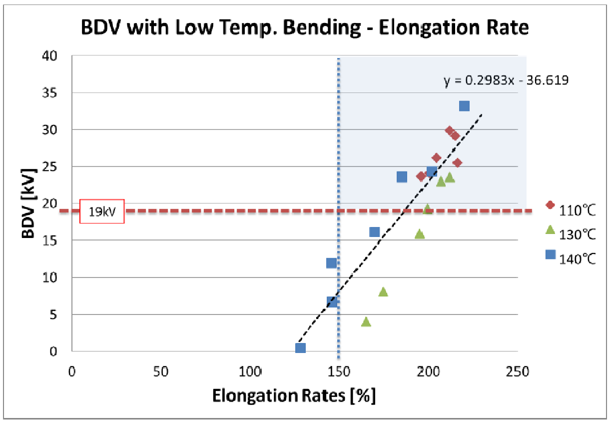

Fig. 5. Correlation between elongation rates and AC breakdown after low-temperature bending test

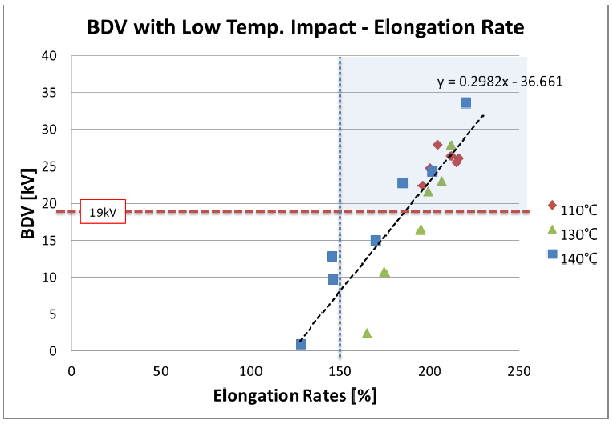

Fig. 6. Correlation between elongation rates and AC breakdown after low-temperature impact test

5.2 Lifetime analysis in consideration of equivalent operating years

As shown in Table 1, accelerated aging factors and lifetimes in equivalent operating years according to temperatures were analyzed using elongation rate data for aged PVC insulation of VCT cables. Moreover, AC breakdown voltages after low-temperature bending test or low-temperature impact test were measured and the correlation between AC breakdown voltage and elongation rate was obtained. In Fig. 7, the results of AC breakdown voltage voltages and elongation rates were rearranged according to the 70℃ equivalent operating years in consideration of accelerated aging factors of 110℃, 130℃ and 140℃. In case of AC breakdown voltage voltages the ratio with elongation rate as shown in Fig. 5 and Fig. 6 were multiplied.

As shown in Fig. 7, AC breakdown voltage data were well fit to the trend line of elongation rates. As mentioned in Table 1, the lifetime limit for the elongation rates of 150% was 9.1 years with the continuous operation at 70℃. However, the lifetime limit for AC breakdown voltage of

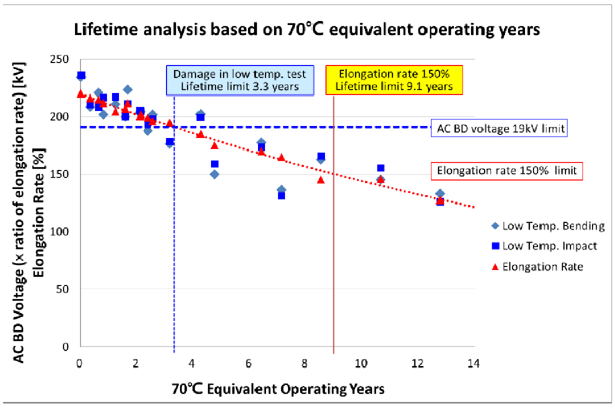

Fig. 7. Analysis of AC breakdown voltages and elongation rates based on 70℃ equivalent operating years

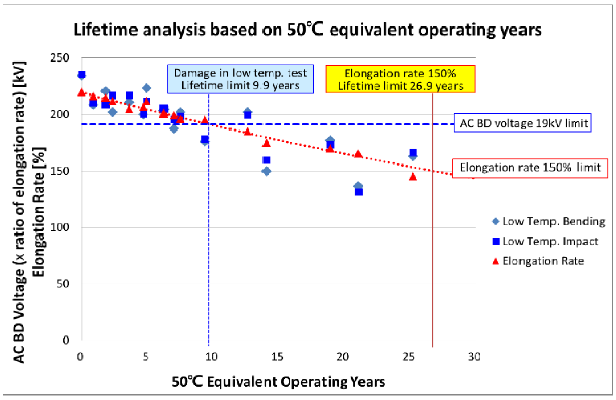

Fig. 8. Analysis of lifetime limit for 50℃ equivalent operating years

19kV was calculated with the value of 3.3 years. The difference between two lifetime limit stems from the different stress application. In case of elongation rate, thermal stress was only applied to the specimens. On the contrary, in cases of AC breakdown, mechanical stress such as bending or impact at the low temperature was added to the thermally aged specimens. Therefore, about one third value in the lifetime of 19kV AC breakdown compared with the lifetime limit for 150% elongation rates was due to the thermally and mechanically multiple stresses.

Lifetime limit of 3.3 years seems to be very short. But, this is the case that the cable operates continuously at maximum permissible temperature of 70℃. In other words, it means that a portable electric machine runs continuously for 3.3 years, which is not an actual situation. However, it is not easy to consider real operation pattern of the machine. Therefore, in this paper, lower operating temperature was assumed to estimate the practical lifetime of the cable.

If it is assumed that the cable operates continuously at 50℃, the thermal lifetime would be considered to be 26.9 years whereas the lifetime limit with thermal and mechanical stress would be obtained to be just 9.9 years as shown in Fig. 8. Similarly, in the assumption of 40℃ operation as shown in Fig. 9, the thermal lifetime would be 42.2 years whereas the lifetime limit with thermal and mechanical stress would be obtained to be 15.7 years. These considerations seem to be more practical for the use of portable electric machines. But, it is recommended to check damages in the cable insulation carefully during the use of the machines.

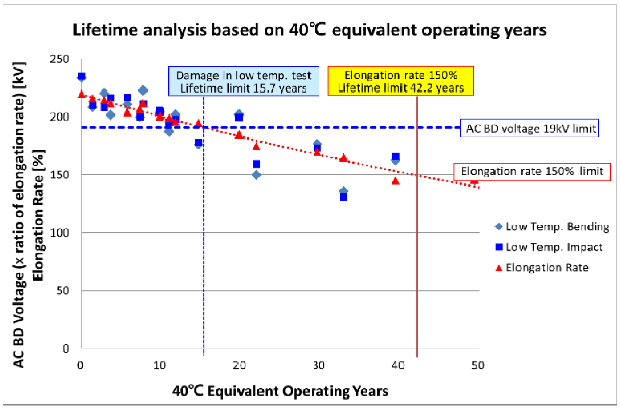

Fig. 9. Analysis of lifetime limit for 40℃ equivalent operating years

6. Conclusion

In this study, the lifetime of VCT cable mainly used in portable electric machines was analyzed through accelerated aging experiments with thermal, mechanical and electrical multiple-stresses and it is concluded as follows.

The elongation rate for degraded specimens was shown to be decreased exponentially with aging time and accelerated aging factors were calculated with aging temperatures based on the Arrhenius relationship. Through Weibull statistical analysis in the AC breakdown voltages for aged cables after low-temperature mechanical tests, it was analyzed that AC breakdown voltages were proportional to the elongation rates and 19kV of the scale parameter in Weibull analysis was suggested as limit value of lifetime.

Considering equivalent operating years at 70℃ continuous operation for VCT cables, the thermal lifetime corresponding to elongation rate of 150% was 9.1 years, whereas the lifetime limit with thermal and mechanical stresses through AC breakdown assessment was calculated with 3.3 years. This difference would be due to the application of mechanical stress. In the assumption of 50℃ and 40℃ operation, the lifetime limit with thermal and mechanical stress would be obtained to be 9.9 years and 15.7 years respectively.

Based on the above analysis, it is possible to perform the lifetime assessment and degradation for low voltage cables using the analysis procedure and experiment with the thermal, mechanical and electrical multiple-stresses. However, it is most important to check damages in the cable insulation carefully during the use of the machines.

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