Analysis of Temperature Conditions Influence on Cables Insulation Operation Life

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Abstract. Electrical equipment fault current interruptions reduce is one of the most important problems of electrical power engineering and diagnostics. Power cables operation life is one of the parameters mostly affecting fault current interruptions on cables. The paper describes the research on thermal degradation of low voltage cables insulating materials and its influence on insulation operation life. The known mathematical models of the insulation aging depending on its temperature are considered. Low voltage cables have an insignificant electrical aging influence, so it is assumed that such cables aging mostly caused by their thermal operating conditions. Experimental research of cables insulation temperature monitoring is performed. Seven weeks of the experiment showed a temperature change between 17°C and 27°C. The mean temperature was 21.9°C. Assuming that cable has normal operation life with an average temperature of 20°C and accounting thermal conditions cable insulation operation life is reduced for about 20%. Such operation life reduce is significant and shows a considerable influence of insulating material thermal deterioration.

1. Introduction
Electrical power equipment technological disturbances reducing is still an important problem. Fault current interruptions can lead power supply disruption of a consumer and electrical equipment failure which causes sufficient economic losses of electrical power companies. Besides, fault current interruptions cause power systems static and dynamic stability reduce. Power supply technological disturbances might appear in power transformers, overhead and cable power transmission lines, rotating machines, electrical furnaces etc. Transformers and rotating machines are being controlled thoroughly because of their importance, high cost and specific diagnostic and maintenance procedures. Power transmission lines diagnostic might be complicated because of defect location difficulties especially in case of considerable line length. Overhead power transmission lines fault current interruptions often connected with insulators flashover. Their cracks are a small part of all technological disturbances on overhead power transmission lines. Fault current interruptions in cable power transmission lines are mostly caused by insulation breakdown. Cable insulation condition highly depends on its operation life and operating conditions. Therefore, cable insulation operation life dependence on its operating conditions continues to be one of the most important research fields of electrical engineering. Besides, operating life control gives useful information for asset management of substations, power plants etc. A common approach of insulating material operation life assessment is using its aging mathematical model. The most considerable results in this field are published in [1–5]. Literature sources analysis shows that insulation operation life mostly depends on aging mechanisms:
• thermal degradation [6, 7];
• partial discharges [8, 9];
• water and electrical treeing [10, 11];
• space charge accumulation for DC cables [12, 13].

However, insulation aging process study is complicated by aging mechanisms dependence on each other. Partial discharge characteristics depend on temperature [14, 15], treeing process also depends on temperature [16, 17]. At the same time, partial discharges cause local insulating material heating in the field of an electrical tree which also increases insulation deterioration. Temperature gradient affects space charge accumulation in the insulating layer [18].

Thus, thermal insulation degradation requires to be researched because of its influence on all the aging mechanisms. Besides, insulating materials thermal aging is not researched enough. Different studies showed contradictory results. The research published in [19] showed that thermal aging must be considered only with electrical aging mechanisms. However, the other research [20] showed a dominant effect of thermal aging. Therefore, insulating materials thermal aging mechanism study is still of high importance.

2. Problem statement

The object of this research is low AC voltage cables insulation. Their electrical aging is insufficient because of high electrical strength margin. The subject of this research is insulating materials operation life and temperature influence on it. Thus, the goal of this research is cables temperature conditions analysis for an assessment of their influence on cable insulation operation life. This goal requires solving the following tasks:

• Temperature monitoring of cable which is in operating conditions;
• Monitoring data analysis and evaluation of cable temperature conditions;
• Assessment of temperature influence on cable insulation using known insulation aging mathematical models.

3. Theory

There are a lot of mathematical models of insulation aging and each of them is built on different approaches. Some of them use a statistical approach and are based on Weibull distribution. The other use physical processes as their basement. This paper considers insulation thermal influence study. Therefore, insulating material aging mathematical models using physical deterioration approach with temperature effect accounting are to be used. They are [2,21]:

- Zhurkov insulation aging model [22,23]:
\[
\tau_o = \tau_0 \exp \left( \frac{w - \chi E}{RT} \right)
\]  (1)

Where \( \tau_0 \) – operation life when exponent tends to 1, \( w \) – structure breakdown activation energy, \( R \) – universal gas constant, \( \chi \) – structure parameter, \( E \) – electrical field, \( T \) – absolute temperature.

- Crine insulation aging model [24,25]:
\[
\tau_o \approx \frac{h}{2kT} \exp \left( \frac{\Delta G - 0.5 \cdot \varepsilon_0 \Delta V E^2}{kT} \right)
\]  (2)

Where \( \varepsilon, \varepsilon_0 \) – relative and absolute dielectric constant of a material, \( \Delta V \) – activation volume in which an electrical field \( E \).

- Arrhenius-IPM:
\[
\tau_o = \tau_0 \exp \left( -BcT \right) \left( E \cdot E_0^{-1} \right)^{(n_0 - BcT)}
\]  (3)

Where \( E \) – electrical field, \( cT = 1/T_0 -1/T \) – conditional temperature stress (\( T \) – absolute temperature, \( T_0 \) – control temperature (room temperature), \( n_0 \) – stress tolerance ratio, \( E_0 \) – electrical field under which it can be neglected, \( \tau_0 \) – operation life with \( T = T_0, E = E_0, B = \Delta W/k \) (\( \Delta W \) – thermal destruction activation energy, \( k \) – Boltzmann constant), \( b \) – parameter of electrical and thermal fields synergism.
• Kuchinsky aging model [21]:

\[
\tau_o = AE^{-n} \exp\left(\frac{W_o}{kT}\right)
\]

Where \(E\) – electrical field, \(W_a\) – activation energy, \(k\) – Boltzmann constant, \(T\) – absolute temperature, \(A\) – constant depending on structure and properties of an insulation, \(n\) – power index depending on an insulation type.

4. Experimental data and their analysis

4.1. Experimental device
The temperature monitoring device used in the experiment is a commercial logger with a multi-zone temperature sensor. The sensor is 5 meters of length and consists of 10 digital temperature sensors which have a distance of 0.5 meters between them. The logger reads the temperature data from each sensor with a one-hour period and writes the data on a micro-SD flash drive. The block diagram of the device is shown in figure 1.

![Figure 1. Block diagram of the temperature monitoring device.](image)

4.2. Measurements
A low voltage cable installed in closed switchgear of a heated building is chosen. Its operating conditions does not contain sufficient thermal effects except cable load and environment temperature. The distributed temperature sensor and the logger were installed on the cable as shown in figure 2.

![Figure 2. Temperature monitoring device installation.](image)

Temperature monitoring was performed in an autumn period: about seven weeks between September and November. The obtained temperature monitoring data are shown in figure 3.
Figure 3. Cable temperature monitoring data.

4.3. Data analysis

The first several weeks the cable temperature has a trend of reduction because of the season temperature reduce outside. Besides, during this period there was no building heating. After it starts the temperature increase cyclic exponential trend appears. Temperature sensors data difference is not significant and is about 1˚C. However, it is more than sensors typical inaccuracy. Temperature change during a day is also insignificant – between 1˚C and 2˚C.

The main goal of the analysis is to calculate the cable insulation thermal degradation degree depending on a temperature increase over normal. Assuming that normal cable operation temperature is 20˚C, that cable insulation temperature is the same in insulation volume and taking into account the average temperature of all sensors for all monitoring time (21.9˚C) the cable operation life reduce can be calculated using equations (1-4):

- Zhurkov insulation aging model:
  \[ \tau_r = \frac{\tau_{21.9^\circ C}}{\tau_{20^\circ C}} = \exp\left(\frac{w - zE}{RT_1} - \frac{w - zE}{RT_2}\right) \]  
  (5)

- Crine insulation aging model:
  \[ \tau_r = \frac{\tau_{21.9^\circ C}}{\tau_{20^\circ C}} = \exp\left(\frac{\Delta G - 0.5 \cdot zE_0 \Delta V E^2}{kT_1} - \frac{\Delta G - 0.5 \cdot zE_0 \Delta V E^2}{kT_2}\right) \]  
  (6)

- Arrhenius-IPM:
  \[ \tau_r = \frac{\tau_{21.9^\circ C}}{\tau_{20^\circ C}} = \exp\left(BcT_2 - BcT_1\right)^{\frac{1}{bE_0} \left(bE_1 - bE_0\right)} \]  
  (7)

- Kuchinsky aging model:
  \[ \tau_r = \frac{\tau_{21.9^\circ C}}{\tau_{20^\circ C}} = \exp\left(\frac{W_a}{kT_1} - \frac{W_a}{kT_2}\right) \]  
  (8)

The calculation results are shown in table 1.
Table 1. Cable insulation operation life reduction for different aging models.

| Aging model     | Operation life reduce, % |
|-----------------|--------------------------|
| Zhurkov model   | 20.3                     |
| Crine model     | 21.3                     |
| Arrhenius-IPM   | 18.6                     |
| Kuchinsky model | 20                       |

5. Discussion
Temperature monitoring data showed considerable temperature change neither during a day (1-2˚C) nor during all monitoring period (17-27˚C). These values of temperature cannot cause significant cable insulation damage especially taking into account maximum operation cable core temperature of 70-90˚C. However, operation life calculation results showed that the average temperature change in 1.9˚C causes operation life reduction of about 20%.

6. Conclusion
Temperature monitoring data showed that the temperature of cable parts can be insignificantly different during a day (1-2˚C). This fact can be explained by the inhomogeneous structure of cable insulation and different influence of environmental air which cools the cable. Temperature difference during all monitoring period is between 17˚C and 27˚C. This is explained by a season environment temperature changes and artificial building heating.

For the first sight, temperature changes cannot cause considerable insulation damage as the temperature is very low relatively cable insulation maximum operating temperature. However, cable insulation operation life reduction assessment using four different mathematical models showed the 20% loss of operation life which is significant.

The calculation and experimental results showed that even insignificant average temperature change can considerably reduce insulating material operation life. Accounting the fact that cable voltage had an insignificant influence on the insulation, thermal degradation has a significant effect on insulating materials operation life.

Cables temperature constant monitoring can be used for its operation life and remaining life calculation and control. These data can be used to predict cable insulation dielectric properties decrease and insulation breakdowns. Besides, this information is useful for asset management of electrical equipment in power supply companies.

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