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INVESTIGATION OF EFFECT OF TEMPERATURE VARIATION IN A HIGH VOLTAGE CABLE ON ELECTRICAL INSULATION

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Abstract: Nowadays, it is known that the high voltage equipment and insulation technology is rapidly growing. Especially, insulation quality issue in the high voltage systems has always been paid attention. Due to severe service conditions and environmental influences, the insulation of high voltage equipment such as cables, insulators, transformers, etc. could be stressed, early aged in time and damaged which may cause undesired power outages. Therefore, electrical parameters of high voltage equipment should be analyzed and measured accurately for heavy operating conditions such as high-temperatures, over-voltages and polluting effects. Generally, dielectric dissipation factor or tangent delta measurements, which give an idea about the good insulation condition, are carried out for most insulation materials. Particularly for high voltage cables, which have an important role in power distribution systems, dielectric losses in insulation material should be analyzed carefully at different temperatures to avoid electrical breakdowns and faults. In this study, dielectric dissipation factor measurements on a 12/20 kV, single core, cross-linked polyethylene (XLPE) insulated high voltage cable are carried out at different conductor temperatures between 20°C and 90°C with temperature steps of 10°C. The test results showed that the conductor temperature significantly affects the dielectric dissipation factor of the cable insulation.

1 INTRODUCTION

For many years, insulation quality issue has been one of the most important study areas in high voltage systems. Generally, the high voltage equipment contains solid dielectric materials which basically insulate the high voltage parts from parts at ground or different potential [1]. High voltage equipment such as cables, transformers, insulators, etc. usually operates under heavy service conditions and could be overstressed thermally and/or electrically which may deteriorate the insulation. Deterioration degree of a dielectric insulation generally introduced with dielectric dissipation factor or tangent delta which give an idea about the lifetime and quality of the high voltage equipment [2, 3].

It is known that high voltage cables play a critical role for energy distribution in power systems. Any electrical fault in cable's insulation could damage the system continuity and cause economic losses [3]. Today, cross linked polyethylene (XLPE) is commonly preferred as insulation in high voltage cables for its favorable physical and chemical properties such as high breakdown strength, thermal resistance and low dielectric losses [4-6]. However, severe long/short term service conditions such as over current and short circuit could thermally affect the insulation and could lead the cable to be early aged. Therefore, dielectric dissipation factor measurements of the high voltage cables' insulation should be carried out attentively for heavy service conditions particularly at different temperatures. Thus, the temperature dependence of the XLPE insulation could be assessed.

Dissipation factor and its temperature dependence analysis in high voltage equipment were discussed in several studies. In the study of P. Werelius and his friends, they investigated the frequency response and temperature dependence of transformer oil to obtain accurate temperature correction factors [3]. G. Tanimoto et al investigated the tangent delta values of polyethylene materials with different density at different temperatures [6]. In the study performed by P. Cichecki et al, tan delta measurements are carried out for a service aged oil-impregnated high voltage cable at different voltage and temperature levels [7]. In the work made by Yongqiang et al, the authors examined the environmental effects (temperature, humidity, etc.) on tangent delta measurement for capacitive equipment [8]. W. Otowski and his friends introduced the temperature and time effect on dielectric dissipation factor measurement for 28 kV high voltage cable junction [9]. In the study carried out by O. E. Gouda and Z. Matter, electrical and physical properties of XLPE insulation were investigated at the temperatures between 20˚C and 160˚C [10].

In this study, dielectric dissipation factor measurements on a 12/20 kV nominal rated, single core, XLPE insulated and non-aged high voltage cable are carried out at different conductor temperatures between 20°C and 90°C with temperature steps of 10°C. Electrical parameters of the cable insulation such as equivalent parallel (R_p) and series (R_s) resistances, parallel (C_p) and series (C_s) capacitances, dielectric losses and dielectric loss index are measured with a digital measurement device named CPC100/CP-TD1 which is shown in Figure 1. Afterwards, the results obtained from the experimental measurements are analyzed to evaluate cable insulation behavior.

Figure 1: Tan delta measurement device.

2 BACKGROUND

2.1 Dielectric dissipation factor

Basically, dielectric dissipation factor (tan delta) in high voltage insulation signifies the losses. An ideal dielectric material is loss-free and generally represent with a pure capacitor. However, when a voltage applied to the dielectric insulation, some kind of active losses occur in it [1]. These losses are as follows,

- Conduction losses (P_c) by insulation resistance,
- Polarization losses (P_p) by orientation boundary layer,
- Ionization losses (P_i) by partial discharges.

In literature, dielectric dissipation factor generally is defined by an equivalent circuit having a capacitor and resistance in parallel or series. The phase difference between voltage and current at an ideal capacitor is 90°. The series/parallel resistances, which represent the losses in the equivalent circuit, causes a small angular deviation in current called delta as shown in Figure 2 and Figure 3 [1, 11].

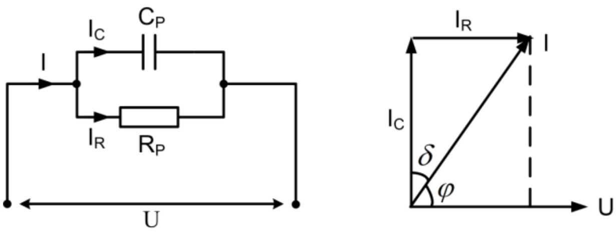

Figure 2: Parallel equivalent circuit and phasor diagram of dissipation factor.

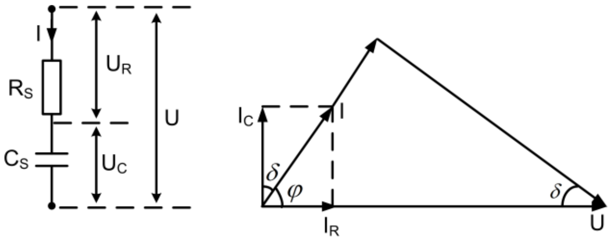

Figure 3: Series equivalent circuit and phasor diagram of dissipation factor.

According to the equivalent circuits above, dissipation factor could be calculated as,

$$tan\ \delta_{parallel} = 1 / \omega \cdot R_p \cdot C_p \quad (1)$$

$$tan\ \delta_{series} = \omega \cdot R_s \cdot C_s \quad (2)$$

where:

ω: angular frequency, in rad/s;
R_p: equivalent parallel resistance, in ohm (Ω);
C_p: equivalent parallel capacitance, in Farad (F);
R_s: equivalent series resistance, in ohm (Ω);
C_s: equivalent series capacitance, in Farad (F).

As it seen from equation (1) and (2), tan delta only depends on the frequency, equivalent resistance and capacitance. However, it is known that the value of these parameters changes with temperature, voltage and frequency. Therefore, validity of these equations is generally acceptable for specified conditions given in standards. Consequently, the real dielectric dissipation factor value should be investigated for varying parameters.

2.2 Dielectric loss index

One of the mostly used parameters to introduce the condition of dielectric insulation in high voltage equipment is dielectric loss index [1, 11]. Dielectric loss index could be calculated as follows,

$$\text{Dielectric Loss Index} = \varepsilon_r \cdot \tan\delta \quad (3)$$

where:

ε_r: Relative permittivity (F/m);
tan δ: Dissipation factor.

To acquire the dielectric dissipation factor of a dielectric insulation, relative permittivity of the insulation material should be calculated as indicated below,

$$\varepsilon_r = C_x / C_0 \quad (4)$$

where:

C_x: capacitance of the cable with real dielectric insulation, in Farad (F);
C_0: geometric capacitance of the cable with vacuum dielectric, in Farad (F).

A geometric capacitance (C_0) is defined as the cable capacitance having vacuum or air instead of dielectric material as insulation between the electrodes. In this study, high voltage cables which have circular cylindrical geometry are used as high voltage equipment. Therefore, capacitance of a coaxial cylindrical electrode system could be calculated as follows,

$$C_0 = 2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_r \cdot l \,/\, \ln (r_2 / r_1) \qquad (5)$$

where:

C_0: geometric capacitance, in Farad (F);
ε_0: dielectric constant of vacuum (F/m);
ε_r: relative permittivity (F/m);
l: cable length, in meters;
r_2: radius of the outer conductor, in millimeter;
r_1: radius of the inner conductor, in millimeter.

By measuring radii of conductors and the length of the high voltage cable, geometric capacitance (C_0), relative permittivity (ε_r) and so the dielectric loss index could be calculated.

2.3 Reference standard (IEC 60502-2)

In the experimental measurements, IEC 60502-2 standard is considered [12].

According to related standard, the following criteria are met for the measurements.

- The ambient temperature, 20°C ± 15°C
- Cable sample length, 10 m – 15 m
- Test voltage (U_0), min. 2 kV
- Cable heating process, current flow through conductor and/or screen

3 EXPERIMENTAL SETUP

In the study, dissipation factor measurements on a 12/20 kV nominal rated, single core, cross-linked polyethylene (XLPE) insulated high voltage cable are carried out at different conductor temperatures between 20°C and 90°C with 10°C temperature steps. Technical specifications of the high voltage cable sample used in the measurements is given in Table 1.

The heating process is performed by flowing current through the cable conductor which is connected to the secondary terminals of a 220V/5V, 5 kVA high current transformer. The flowing current through the cable conductor is controlled by a 5 kVA, 0-220 V variac connected to primary winding of the high current transformer. The current is measured by a clamp ammeter of 1000 A. When the current flows through the cable, the surface temperature of the cable conductor is measured with a 289/FVF Fluke digital multimeter at ±1% + 1°C measurement sensitivity.

Table 1: Technical specifications of cable sample

Parameter	Value
VDE Code	N2XSY
Nominal voltage (kV)	12 / 20
Nominal cross-section (Al) (mm^2)	1x95/16
Diameter of conductor (mm)	6.18
Conductor DC resistance (at 20°C) (ohm/km)	0.253
Operating inductance (mH/km)	0.65
Operating capacitance (μF/km)	0.23
Current carrying capacity (in air) (A)	378
Cable length (m)	11.7
Overall diameter (mm)	38
Status	Non-aged

To perform a precise measurement, the temperature is measured from the both conductor terminals of the cable sample to realize the different connection resistances and control the temperature at the buses of high current transformer. During the measurements, temperature difference at the both conductor terminals is kept around ±1°C. Before the tan delta measurements are carried out, conductor temperature is kept around the specified value about one hour to obtain thermal stability. Moreover, outer sheath of the cable is coated with a heat insulation material. Thus, the cooling of the heated cable is slowed down.

All measurements are realized at the specified conductor temperature with ±0.5°C sensitivity. Three measurements were performed for all parameters and the average values are calculated. The experimental setup is given in Figure 4.

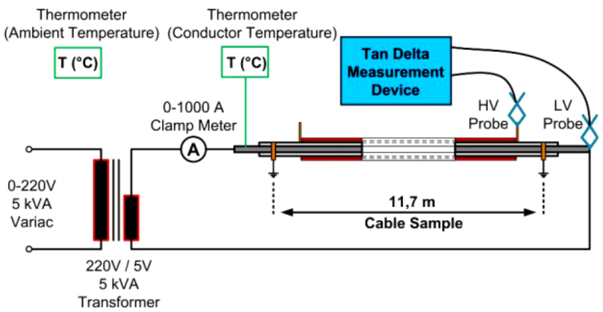

Figure 4: The experimental setup.

In all measurements, CPC-100/CP-TD1 digital tan delta measurement device is used. The device has two probes as high voltage and low voltage. The high voltage output supplies up to 12 kV alternating voltages at 0 – 400 Hz frequency ranges. As seen in Figure 4, the high voltage output is connected to the copper screen and the measured data is acquired from the cable conductor with low voltage probe. Additionally, a copper tape is wrapped over the XLPE surfaces at the both terminals of the cable. Thus, the measured data is protected from distortion effects of surface discharges. The connections made for the measurement is shown in Figure 5.

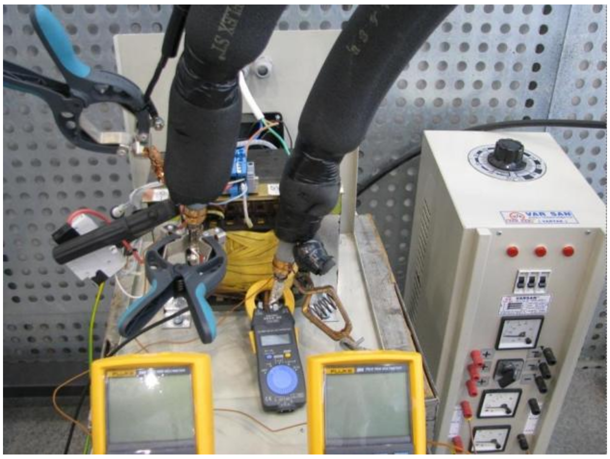

Figure 5: The measurement connections.

According to the IEC 60502-2, the ambient temperature of the laboratory is kept around 20°C ± 15°C and the average atmospheric conditions during the measurements are given in Table 2.

Table 2: Atmospheric conditions of the laboratory

Measured Data	Value
Temperature (°C)	19.5
Relative Humidity (%)	34
Atmospheric Pressure (mmHg)	765.44

4 MEASUREMENT RESULTS AND ANALYSIS

The dielectric parameter measurements of a XLPE insulated high voltage cable are carried out at different conductor temperatures between 20°C and 90°C at 10 kV test voltage. The results obtained from the measurement are given in Table 3 and Table 4.

Table 3: Measured data at the different conductor temperatures

Temperature (°C)	U (kV)	tan δ (%)	Pk (mW)	I (mA)
20	10	0.0990	88.0	9.0640
30		0.0949	86.0	8.9648
40		0.0900	79.6	8.8164
50		0.0945	82.3	8.6450
60		0.0993	83.2	8.4871
70		0.1028	85.2	8.2658
80		0.1159	87.3	7.6130
90		0.1206	92.6	7.5925

Table 4: Measured electrical parameters of dielectric insulation at the different conductor temperatures

Temperature (°C)	U (kV)	Cp ≈ Cs (nF)	Rp (GΩ)	Rs (Ω)
20	10	2.88429	1.164	1037.7
30		2.85255	1.169	1053.1
40		2.80544	1.258	1001.4
50		2.75079	1.225	1088.8
60		2.70052	1.202	1146.5
70		2.63010	1.176	1247.0
80		2.42253	1.142	1494.0
90		2.41589	1.081	1616.4

As it is seen from the measurement results, variation of conductor temperature has a significant effect on the dielectric insulation. The changing of tan delta value of the dielectric insulation according to the different conductor temperatures is given in Figure 6.

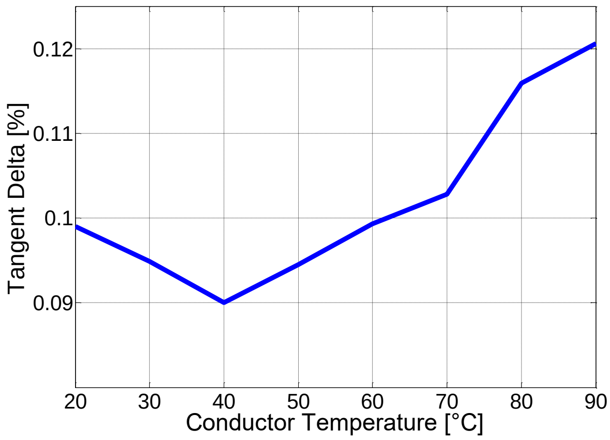

Figure 6: The relation between tangent delta and conductor temperature.

It is seen from the Figure 6 that, there is a decrease in tan delta value from 20°C up to 40°C. At 20°C conductor temperature, tan delta value is about 0.99 and towards 40°C conductor temperature; this value is decreasing about 9.1 percentages. This means that the dielectric losses in the XLPE insulation are decreasing and the insulation becomes steadier around 40°C. From 40°C to 90°C, tan delta value is increasing with the increased conductor temperature. Tan delta value at 90°C conductor temperature is 1.34 times greater than the value at 40°C. Thereafter about 40°C conductor temperatures, the dielectric losses in the insulation material are rapidly increasing as shown in Figure 7.

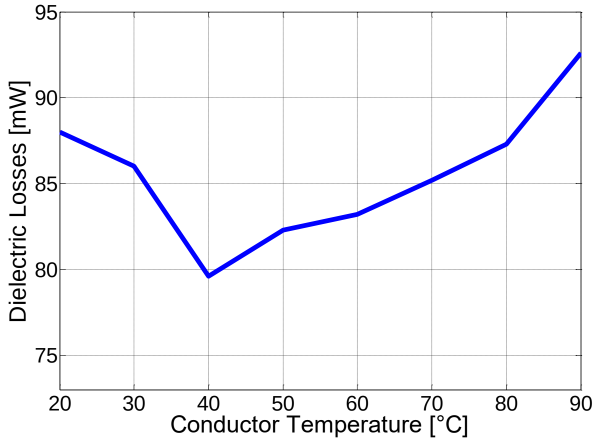

Figure 7: The relation between dielectric losses and conductor temperature.

In Figure 7, dielectric losses in the insulation material are decreasing from 20°C up to 40°C. Thereafter, up to 90°C conductor temperature, the tan delta value is increasing. For higher conductor temperatures, dielectric losses deteriorate the insulation further. It is obvious that there is an affiliation between tan delta and dielectric losses. For this reason, the curve in Figure 7 is similar with the tan delta curve shown in Figure 6.

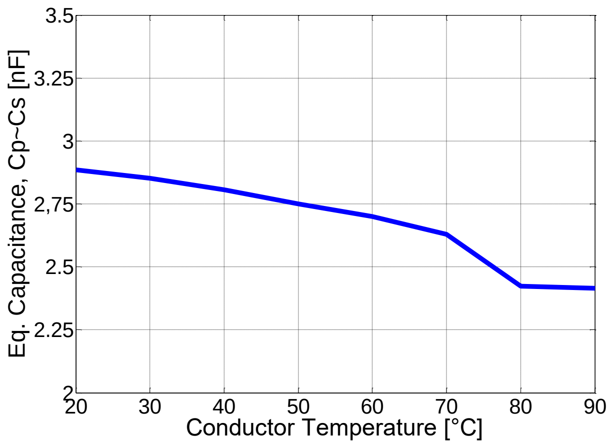

Figure 8: The relation between conductor temperature and equivalent capacitance of dielectric insulation.

Variation of the cable capacitance with the cable conductor temperature is shown in Figure 8. The capacitance value is slightly decreasing with the increased conductor temperatures. When the temperature changes from 20°C to 90°C, capacitance value of the cable is decreasing from 2.88429 nF up to 2.41589 nF. The dielectric insulation loses its 16% electrical capacity from 20°C up to 90°C temperatures.

Values of dielectric loss index determined at different conductor temperatures are given in Table 5. Dielectric loss index of the high voltage cable is determined by using the equations (3), (4) and (5).

The radii of the inner conductor (r_1) and the outer conductor (r_2) are measured as 7 mm and 12.7 mm, respectively.

Table 5: Values of dielectric loss index measured at different conductor temperatures

Temperature (°C)	C_x (nF)	C_0 (nF)	Tan δ (%)	Loss Index (%)
20	2.88429	1.09266	0.0990	0.26133
30	2.85255		0.0949	0.24775
40	2.80544		0.0900	0.23108
50	2.75079		0.0945	0.23791
60	2.70052		0.0993	0.24542
70	2.63010		0.1028	0.24745
80	2.42253		0.1159	0.25696
90	2.41589		0.1206	0.26665

It is clearly seen from the Figure 9 that, dielectric loss index shows quietly similar behaviour with tan delta shown in Figure 6.

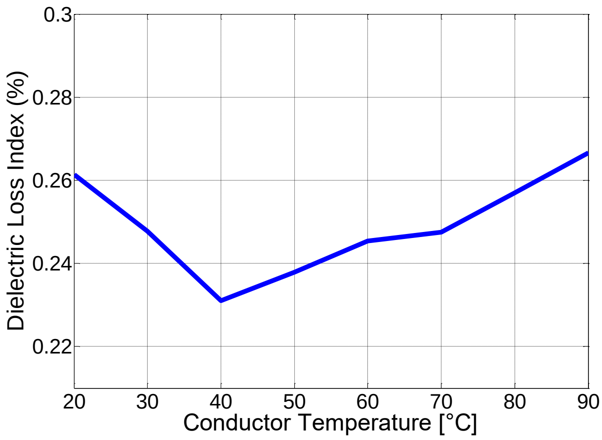

Figure 9: The relation between conductor temperature and dielectric loss index.

5 CONCLUSION

In the study, dissipation factor measurements on a 12/20 kV nominal rated, single core (Al), cross-linked polyethylene (XLPE) insulated and non-aged high voltage cable are performed at different conductor temperatures between 20°C and 90°C with temperature steps of 10°C.

The results showed that, temperature changes in the dielectric insulation are seriously affect the insulation quality of high voltage cable. Especially after 40°C conductor temperature, dielectric losses and tan delta value of the insulation are rapidly increasing. Besides, dielectric insulation loses its electrical capacity for higher temperatures. Similarly, dielectric loss index value, which is an important parameter for the calculation of dielectric losses, is increasing for higher temperatures. For this reason, higher conductor temperatures deteriorate dielectric insulation quality of high voltage cables, which generally operate at nominal current. Thus, increased dielectric losses in a high voltage cable with increasing temperature may cause electrical breakdowns and lead early ageing.

Consequently, temperature variations have a crucial effect on the lifetime of high voltage cables. When it is considered that electrical load and so the current in a power system are not steady, the estimated lifetime of the high voltage cable for normal operating conditions will not be reliable. Therefore, temperature analysis of high voltage cables should be done more accurately and the research studies on this subject should be developed.

6 ACKNOWLEDGMENTS

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