Application of dielectric loss measurements for life consumption and future life estimation modeling of oil-impregnated paper insulation in HV power cables

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Abstract

This thesis gives a description of diagnosing life consumption and future life estimation of oil-impregnated paper insulated cable by using dielectric loss value. Dielectric loss values were investigated at different temperatures and different electrical field intensities in the laboratory. Based on laboratory measurements, a program was built; it can calculate the life consumption of paper oil-impregnated insulation by on-site dielectric loss measurements. Thermal aging was also taken into account for life consumption calculation in the program as an additional criterion. After that, future life estimation was calculated based on the result of life consumption and thermal aging theory in the program.

The introduction chapter gives a description of oil-impregnated paper insulated cable. It also introduces the life time of the cable. Furthermore, available diagnostics methods are introduced. Because dielectric loss value is a useful tool to assess the condition of oil-impregnated paper insulation, this was chosen for diagnosing the life consumption of oil-impregnated paper insulation in this thesis.

In chapter two, the characteristics of the structure of porous paper and mineral oil are introduced. Four stress factors which influence the insulation are mentioned. In the lab, only the electrical stress and thermal stress were investigated, so the influences of electrical stress and thermal stress on the insulation are introduced in detail. In this part electrical aging and thermal aging are also introduced.

Chapter three gives information about the measurements of dielectric loss value in the laboratory. The goals of these tests were to analyze the relation between life consumption and dielectric loss value at constant temperatures and constant electrical field intensities. The method of testing and the test object are described. The results of the measurements are presented and explained: the investigations of the influence of electrical field intensity and temperature on the oil-impregnated paper insulation are described; based on this, the relation between dielectric loss value and life consumption is analyzed.

Chapter four introduces a program which was built for life consumption and future life estimation calculation. The methods of calculating insulation life consumption by dielectric loss value and operational life consumption by thermal aging are described. After that future life estimation calculation based on the life consumption result is introduced.

In chapter five, the program mentioned in chapter four was verified by the dielectric loss values of a bad condition cable and a good condition cable. The results of life consumption and a future life estimation of the two different cables are shown. In the last part future load model of the two different cables is built, the future life estimations are compared for different loads.

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1 Introduction

1.1 Introduction to HV oil-impregnated paper insulated cables

Oil impregnated papers have been used since the earliest days of cable development and even today constitute one of the most extensively used cable insulations. Oil paper insulation is still regarded as perhaps the most reliable composite insulation system for cable applications[1]. They have a longer service record than any other types available. Oil-impregnated paper has good heat transfer properties, low dielectric loss and high breakdown strength, and as a result, has been used as the primary insulation in electrical power equipment. Figure 1.1 shows the cross section of oil-impregnated paper insulation cable.

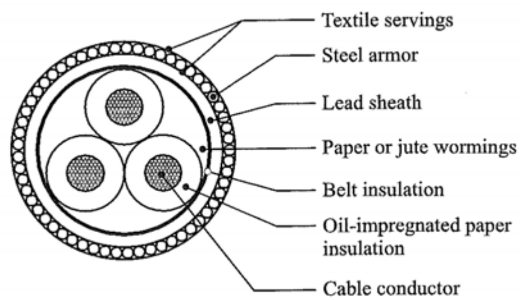

Figure 1.1 Cross section of three-conductor oil-impregnated paper power cable [1]

High voltage cable insulated with oil-impregnated paper can be divided into two main categories: oil-filled cables and gas-pressured cables. Oil-filled cables can be used for voltage up to 500kV, gas-pressured cables are used for voltage up to 275kV [2]. In figure 1.2, the oil-filled cables are shown. In figure 1.3, the gas pressured cables are shown.

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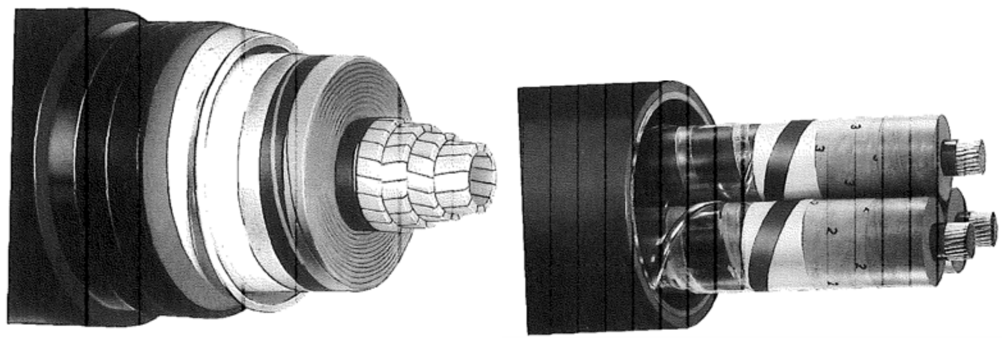

Figure 1.2 oil-filled cables [2]
1) Low pressure oil-filled cable; 2) High pressure oil-filled cable

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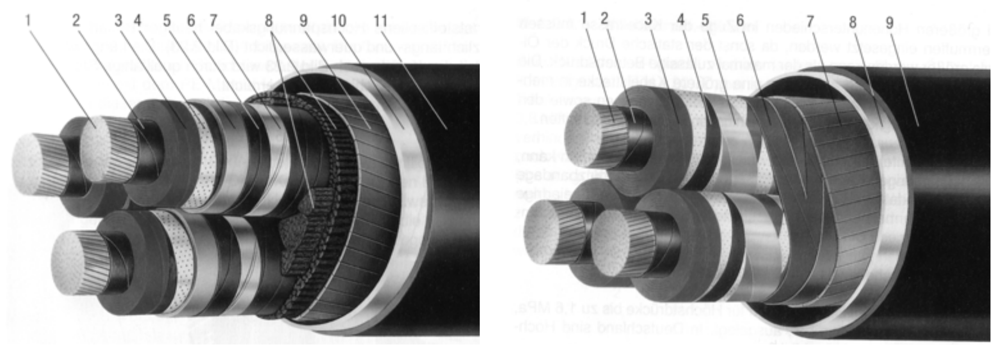


1) Copper conductor
2) Insulating tape
3) Oil-impregnated paper insulation
4) Metallized paper tape, carbon black paper intercalated with carbon black paper
5) Woven copper fabric tape
6) Paper tape/Metal insulation shield
7) Reinforced lead/Metal tape
8) Metal shield/paper or jute fillers/rubber coating
9) PCV jacket/ Reinforced elliptical lead sheaths
10) Metal shield
11) PCV jacket

Figure 1.3 gas pressured cables
1) Internal gas pressure cable; 2) External gas pressure cable

1.2 Life time of oil-impregnated paper insulation

When the HV power cable has been in operation for tens of years (e.g. 40 years), further loading will reduce the life and accelerate the aging process even more. In this way, more and more attention must be paid to such a HV system. During operation, voltage and frequency applied on the cable insulation are constant. When the current flows, heat dissipates in the conductor. If other losses in the conductor are ignored, the temperature difference between conductor temperature and ground temperature is proportional to the square of the current. Thus the temperature difference between maximum conductor temperature and ground temperature is proportional to the square of maximum current [4]. The equation can be written as:

$$\frac{T_{conductor} - T_{ground}}{T_{\max} - T_{ground}} = \frac{I^2}{I_{\max}{}^2} \quad (1)[7]$$

$$\frac{I^2}{I_{\max}{}^2} = (load\%)^2 \quad (2)$$

From the above two equations, it can be seen that increasing the load will raise the temperature of the conductor. The relation between the load and cable temperature is:

$$T_{conductor} = T_{ground} + (T_{\max} - T_{ground}) * (load\%)^2 \quad (3)$$

Where:

$T_{conductor}$ is the cable temperature

T_{ground} is the ground temperature

T_{max} is the maximum temperature of the cable

Load% is the percentage of the load.

Due to the thermal stress caused by the load applied on the cable, the relation between degradation rate of cable insulation and temperature can be described by Arrhenius law [3]:

$$k = A \cdot e^{(-Ea/R \cdot T)} \qquad (4)$$

Where:

k is the reaction rate coefficient

A is constant (maximum speed reaction)

Ea is the activation energy (energy that has to be delivered to start the reaction)

R.T is the average energy the molecule has at certain temperature

R is the molecule gas constant (8,314472 [J $K^{-1}mol^{-1}$]

T is the absolute temperature

According to Arrhenius law, the degradation rate of the cable insulation increases exponentially with cable temperature. For the oil-paper insulation, the parameters for calculating the degradation rate by cable temperature are determined by Montsinger, this is so-called the law of Montsinger. Montsinger law gives a relation between the yearly degradation rate and cable temperature. Thermal degradation of Monstinger is shown below:

$$D_{year} = D_{to} * 2^{(\frac{T_{conductor} - 15}{T_d})} \quad (5)\ [3]$$

Where:

D_{year} is yearly degradation

D_{to} is yearly thermal degradation at 15°C

$T_{conductor}$ is cable temperature

T_d is temperature difference to get double degradation

In Table 1.1, the results of calculating cable life time, by using Monstinger law are shown. The cable type is external gas-pressure cable and the ground temperature regards as 10°C.

$T_{conductor}$ [°C]	Load [%]	Yearly degradation rate [%]	Life [years]
10,5	10	0,78	127
12	20	0,85	117
14,5	30	0,97	100
18	40	1,17	85
22,5	50	1,49	67
28	60	2	50
34,5	70	2,82	35
42	80	4,2	23
50,5	90	6,6	15
60	100	11	9,1

Table 1.1 Cable life time, yearly degradation and cable temperature calculated by load

In the table it can be seen that cable yearly degradation increases with load increase, so the life time decreases when load is increased. When the load on the cable is 30%, cable life time is 100 years, this is twice as long as when the load is 60%. When load is 10%, life time is 127 years, it's more than 10 times life time when the load is 100%.

Figure 1.4 shows the relation between cable life time and percentage of load when the ground temperatures are 5°C, 10°C and 15°C. Cable life time shows an inversely proportional relation.

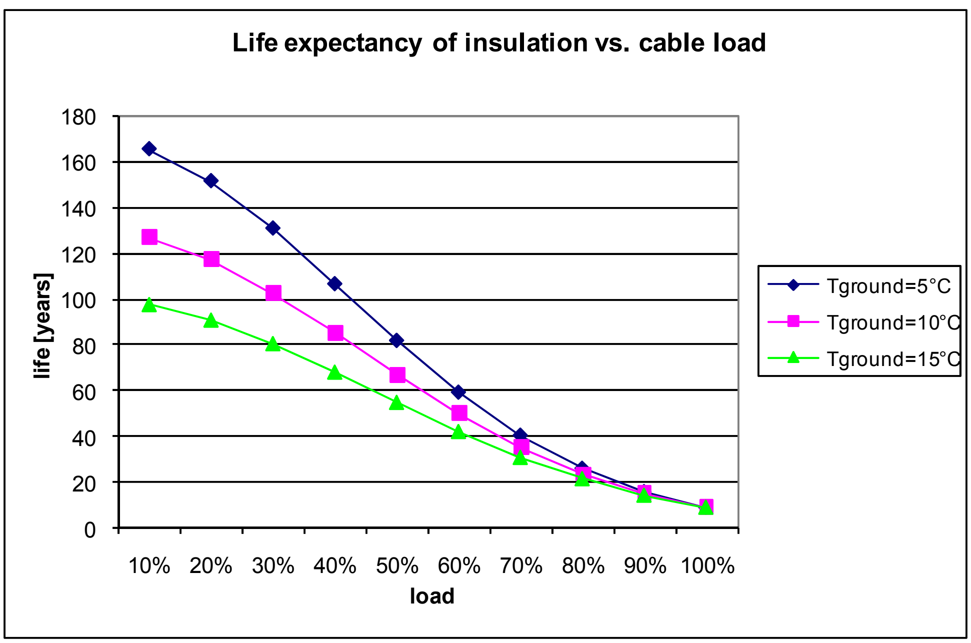


Figure 1.4 Relation between life expectancy and cable load at different ground temperature

1.3 Available diagnostics for HV cables

The aim of diagnostics is to provide information about insulation deterioration. Depending on the kind of test, it can provide information about the overall condition of the whole cable system or indicate the location defects that may cause failures in the future. Even though HV cables are tested by the manufacturer after the production process is finished, some defects still arise during transport, installation or service. Moreover, as failures become troublesome users desire to know before hand, whether the cable is able to operate in a certain condition (e.g. maximum load) for a certain period of time. The desire to avoid such failures, may force users to perform periodic tests on cables operating in the field [18].

The available on-site diagnostic methods for aged HV power cable with paper/oil insulation [4] are:

a) dielectric loss measurements (tanδ) - indication of condition cable insulation
b) recovery voltage method (RVM)
c) partial discharge (PD) measurements - detection of local faults
d) DC sheath test – condition of non-metallic outer sheath
e) oil analysis – condition of the oil and indication for aging and defects in insulation
f) visual inspection of accessories – detection of pollution, aging and damages
g) inspection of earthing system – check of layout and resistances
h) inspection of hydraulic system – check on leakages, working of pressure gauges and alarm settings
i) determination of impregnation coefficient – presence of free gas in the cable insulation
j) G-value measurement – thermal resistance of soil around the cable

In this thesis, the research object is oil-impregnated paper insulation. For paper insulation, dielectric loss measurement is a clear indicator of insulation deterioration. Thus for diagnosing the condition of oil-impregnated paper insulation, dielectric loss measurement will be described in this thesis.

1.4 Dielectric loss of a cable

When an insulation material is subjected to an A.C. voltage, losses occur in the material. They are caused by a loss component Ir of the dielectric current, this component makes an angle δ with the purely capacitive current Ic, and equals Ir=Ic·tanδ [4]. The phasor diagram and equivalent circuit of a cable dielectric is shown in Figure 1.5.

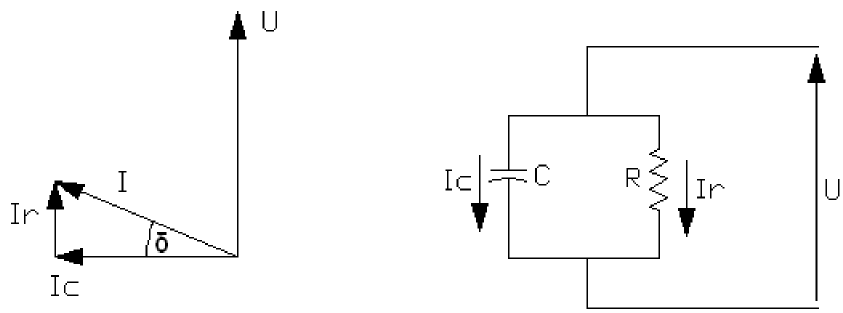


Figure 1.5 Phasor diagram and equivalent circuit of a cable dielectric

The tangent of the angle is a measure for the dielectric losses W:

$$W = U \cdot I_C \tan\delta = U^2 \omega C \tan\delta \ (6)$$

Where:
C – capacitance of the insulator
U – phase voltage

The losses are proportional to the loss tangent tanδ,

$$\tan\delta = \frac{I_r}{I_c} = \frac{1}{\omega \cdot R \cdot C} \quad (7)$$

1.5 Problem definition

Diagnosis of service aged cables is important from the point of view of supporting decisions about operation, maintenance and replacement of the cables. The condition of the oil-impregnated paper insulated cables can be determined by on-site diagnosis. In particular, dielectric loss (tanδ) can be measured in function of test voltage; the tanδ value indicates the condition of the cables. To be able to determine the life consumption and future life estimation, a model is needed to relate dielectric loss in function of test voltage with life expectancy. Therefore the problem of this thesis can be described as follows:

1. During laboratory investigation, the tanδ diagnosis can be performed at different voltages and different temperatures. So the dielectric losses behavior in function of voltage and temperature can be determined.

$$lab\_\tan\delta = f(U,T) \quad (8)$$

2. The insulations used for laboratory measurements are subjected to accelerated aging. Thus a model can be established as tanδ value in function of life consumption and voltage. Using this model, the life consumption can be calculated by tanδ value and voltage from the laboratory measurements.

$$life\_consumption[\%] = f(\tan\delta, U) \quad (9)$$

3. During on-site diagnosis, the tanδ value can be measured in function of voltage.

$$field\_\tan\delta = f(U) \quad (10)$$

4. The on-site measurement tanδ values can be used for the life consumption calculation provided by the laboratory data to verify the model.
5. The thermal instability/stability can be determined from the relation between the tanδ value and temperature. The temperature rise of the insulation mainly depends on the load. Thus the relation between the tanδ value and load can be determined.
6. Thermal aging of the insulation can be determined by Arrhenius Law and Montsinger Law. The life consumption calculated by thermal aging can be used to compare and combine with the life consumption calculated by the method using tanδ.

7. Future life estimation of the cables is also based on values determined by Arrhenius Law and Montsinger Law, it can be calculated by the life consumption from 4) and 6).

The model used for the diagnosis of service aged oil-impregnated paper insulation cables, is very important for further operational decisions about high voltage oil-impregnated cables.

1.6 Scope of the study

The following statements provide an outline of this study:

1 There are still service-aged cables with oil-impregnated paper insulation in use, it's necessary to know the remaining life of the cables.

2 Dielectric loss value is a clear indicator of the condition of HV cables.

3 During the on-site diagnosis, dielectric losses in function of test voltage ($\tan\delta = f(U)$) can be measured.

4 During the laboratory investigation on paper samples, dielectric losses in function of test voltage ($\tan\delta = f(U)$) and dielectric losses in function of temperature ($\tan\delta = f(T)$) can be measured.

5 The actual condition of service-aged oil-impregnated power cables can be assessed based on 3).

6 The information of 4) can be used to make decisions about operational availability and reliability, about the necessary maintenance and or replacement steps.

7 Investigation of dielectric loss behavior in function of temperature. Observation of thermal parameter of the insulation, thermal stability/instability transition.

8 A program can be built to calculate life consumption and future life estimation.

1.7 Experimental approach

For this thesis an experiment was conducted by carrying out the following steps:

1. Read relative papers and books to know the factors influencing the dielectric loss in oil-impregnated paper insulation.

2. Measure periodically dielectric loss of oil-impregnated papers at different voltages and different temperatures., for samples subjected to accelerated and thermally controlled aging.
3. Collect and evaluate the results from the experiments.
4. Analyze the results from the experiments, establishing the model of dielectric loss $\tan\delta$ in function of electrical field intensity, temperature and life consumption ($\tan\delta=f(E,T)$).
5. Determine the model of dielectric loss in function of test voltage and life consumption.
6. Form a formula of life consumption in function of relative $\tan\delta$ value by data analysis fitting.
7. Make a program that can achieve outputting insulation life-consumption by inputting $\tan\delta$ value of oil-impregnated paper insulated cable and test voltage.
8. Take into account operational life consumption calculated by thermal model and $\tan\delta$ model.
9. Diagnose the future life estimation of oil-impregnated paper insulated cable based on the life consumption results.

2 Oil-impregnated paper insulation

To diagnose the life expectancy of paper insulated cable, it is necessary to understand the factors which are contributing to the ageing. The goal of this chapter is to come to an understanding of the ageing process of oil-impregnated paper insulation. To understand this process first a description of the molecular structures of the paper and oil and the impregnation process are given in chapter 2.1 and 2.2. From here a review into the factors which have a detrimental influence on the insulation is given.

2.1 Structure of oil-impregnated paper insulation

The insulating capacity of oil-impregnated paper insulation is determined by their molecular structures. In the next two paragraphs a description of paper and the oil used to impregnate the paper is given on a molecular level.

2.1.1 Structure of paper

Kraft papers are used in oil-impregnated paper insulation for cable application. Kraft papers consist of cellulose fibers felted together to form mechanically strong sheets. The paper composition is defined by the general chemical formula $C_{12}H_{20}O_{10}$. The cellulose molecules of the paper fibers consist of a series of glucose repeating units arranged in cellobiose pairs, as shown in Figure 2.1[1].

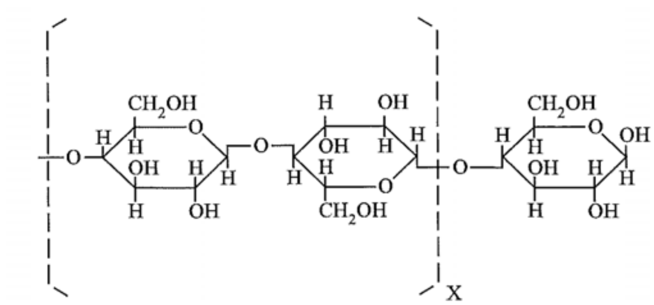


Figure 2.1 Molecular structure of cellulose.

The paper cellulose does not form a homogeneous solid material, but it's always in the form of a porous material with a greater or lesser air content. The pores of the paper tend to absorb fairly large amounts of moisture from the atmosphere. The OH grounds in the cellulose molecule ensure that the absorbed moisture remains bound relatively firmly to the cellulose structure. This moisture has a particularly strong detrimental effect on the dielectric properties of the paper. Most of the moisture, however, can be removed by heating the paper under vacuum.

2.1.2 Structure of oil

The insulating oils which are used as impregnating medium in conjunction with the kraft paper comprise naphthenic, paraffinic, and aromatic constituents. Molecular constituents of mineral cable insulation oil is shown in figure 2.2. Each given cable insulating oil comprises a variety of molecular sizes and structures[1].

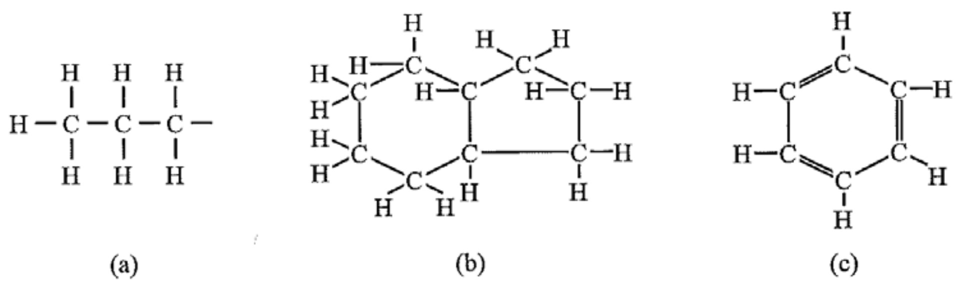


Figure 2.2 Molecular constituents of mineral cable insulation oil: (a) paraffinic structure; (b) naphthenic structure; (c) aromatic structure

Oil conductivity and viscosity depend on molecular size and structure in the oil. Increase of oil conductivity can cause the increase of dielectric loss of the oil. The oil viscosity determines the mobility of the oil within the cable insulating systems. Decrease of oil viscosity may cause void formation which can lead to partial discharge.

2.2 Impregnation process

The goal of the impregnation process is to optimize the insulation properties of the oil impregnated paper. Prior to use as a high-voltage cable dielectric, the materials chosen for the paper and impregnating media have to be suitably treated to achieve satisfactory electric properties. Therefore the impregnation process consists of two steps: material pretreatment and the impregnating itself.

1. Material pretreatment

Moisture in particular has an adverse effect on both the dielectric and electrical properties of the system; it increases the dielectric loss and reduces the breakdown strength. Moisture therefore has to be removed carefully from the components of the dielectric; the same also applies to the air inside the pores of the paper. It is known that the paper moisture falls dramatically as the temperature increases, but mechanical properties of the paper will be impaired at too high temperatures. Therefore the paper is dried in a vacuum tank at a high temperature. The optimum dry conditions are around 120°C and in a tank vacuum of 10^{-2} to 10^{-3} mbar [2].

The oil will be subjected to a drying, degassing and deionization process.

2. Impregnating

The paper is saturated with impregnating oil. This process usually is performed at elevated temperature, which increases gas evaporation and diffusion processes and reduces viscosity of the impregnating medium. This facilitates paper penetration by the impregnating medium.

2.3 Influence of stress factors on impregnated paper insulation properties

The stress factors which influence the insulation are electrical stress, thermal stress, mechanical and environmental stress. In table 2.1, the stress factors that affect cable insulation systems are shown:

Electrical	Thermal	Mechanical	Environmental
- voltage (dc, ac, impulse) - frequency - current	- temperature - low, high ambient - maximum temperature - temperature gradient - temperature cycling	- gases - lubricants - water/humidity - corrosive chemicals - radiation	- bending - tension - compression - torsion - vibration

Table 2.1 stress factors that affect cable insulation systems [9]

The effects of these stress factors on the insulation are shown in table 2.2:

Electrical	Thermal	Mechanical	Environmental
- partial discharge - electrical treeing - dielectric losses increase - charge injection - intrinsic breakdown - overheating	- hardening, softening, loss of mechanical strength, embitterment - dielectric loss increase - shrinkage, loss of adhesion, separation, delimitation at interface - swelling - loss of liquids, gases - conductor penetration - rotation of cable - formation of spots, wrinkles - increase migration of components - movement of joints, terminations	- mechanical rupture - loss of adhesion, separation, delamination at interface - loss/ingress of liquid, gases	- increased temperature, thermal aging, thermal runaway - increase losses and electrical tree - flashover - hardening, softening, loss of mechanical strength, embrittlement

Table 2.2 effects of these stress factors on the insulation [9]

During laboratory investigation, the samples are subjected to different levels of electrical and thermal stress. In 2.3.1 and 2.3.2, the influences of electrical stress and thermal stress on impregnated paper insulation are discussed more in detail.

2.3.1 Influence of electrical field on impregnated paper insulation properties

When an electrical field is applied to the insulation, the molecules of the insulation are electrically strained, and the material is said to be polarized. If polarization of one molecule increases, the field strength in its immediate vicinity increases which results in the additional polarization in the neighboring molecules and further strengthening of the field. Four polarization mechanisms are shown in Figure 2.3.

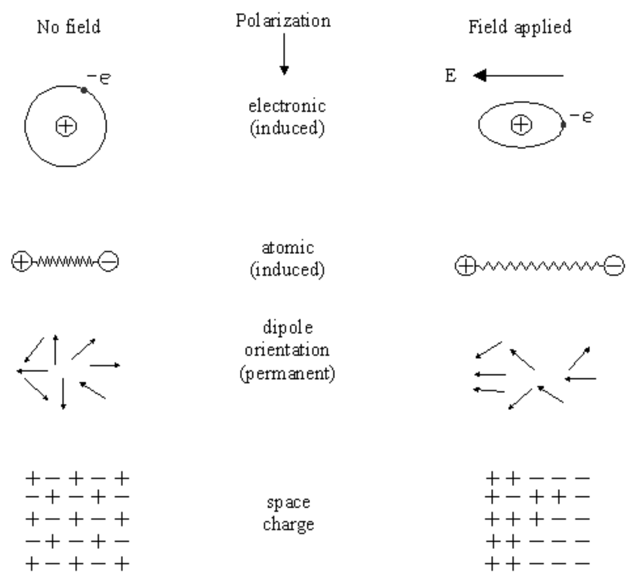


Figure 2.3 Polarization mechanisms [7]

1) Induced electronic polarization is caused by the displacement of electronic charge with respect to the positive charge nucleus of the atom.
2) In the case of atomic polarization, in the binding of two atoms some electronic charge can be transferred from one partner to the other. In this way, two atoms become ions which response to application of electrical field by atomic polarization.
3) If in the material there is some charge asymmetry, it usually causes permanent dipole moments. The alignment of molecular dipoles may be achieved by rotation of groups of molecules. The higher temperature the higher the mobility of dipoles when subjected to electric field.

4) Space charge polarization arises from the fact that ions and electrons have limited mobility in dielectric materials. Charge is usually “trapped” in amorphous regions. When an electric field is applied, displacement of charge is observed and this produces macroscopic dipoles [7].

From a macroscopic point of view, conduction in impregnated paper may be described as due to the motion of ions in oil, when an electric field is applied [9]. This is shown in Figure 2.4. Thus the tanδ value change with electrical field intensity can be explained as ionic motion in oil-filled paper pores in the insulation. The tanδ value exhibits an increase with applied voltage. This is caused by the fact that a rising applied field increasingly segregates the oppositely charged ions, as explained above, due to atomic induced polarization.

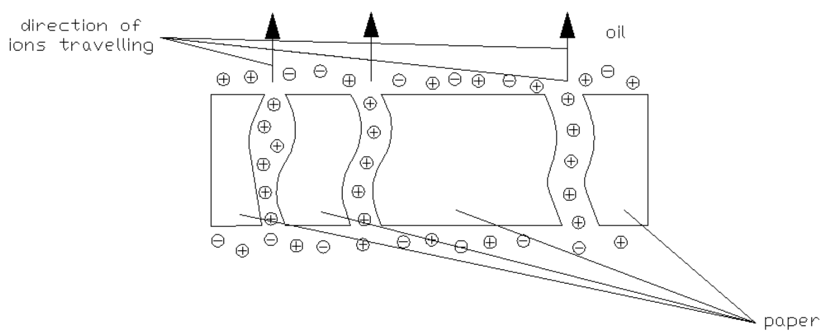


Figure 2.4 Ions travelling trough oil-filled pores in impregnated paper insulation

However, tanδ may also fall with the field due to interfacial polarization effects as ionic charge becomes trapped or piled-up at dielectric interfaces having unequal conductivities and real permittivities.

Particular cases of the space charge or interfacial polarization process are often referred to as the Garton effect. These mechanisms occur within the oil-filled pores of kraft paper insulation, as the ionic motions become limited by the boundaries of the pores. Figure 2.5 shows that Garton effect happens in the oil space in the paper pores. The ions in oil will collide with paper fiber within the time of AC half cycle when ion movement distance in AC half cycle is larger than the oil space. When the velocity increases to a certain value, the tanδ decreases with electrical filed intensity due to Garton effect.

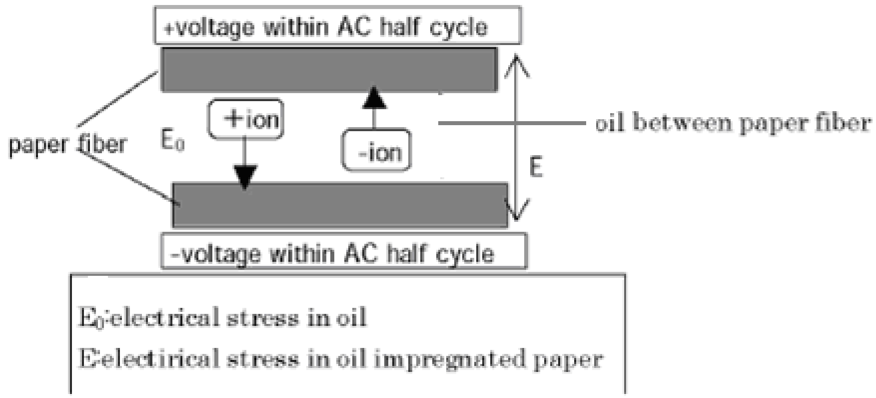


Figure 2.5 Schematic image of Garton effect [6]

2.3.2 Influence of temperature on impregnated paper insulation properties

For new impregnated paper insulation, there is no increase of dielectric loss value with temperature; this is due to the fact that there is a lack of conducting particles.

For aged impregnated paper insulation, an increase of temperature enhances ionic losses in oil-paper systems due to the decrease in the oil viscosity with temperature. In Figure 2.4, it is already shown that tanδ change can be explained as ionic motion in the oil-filled paper pores in the insulation. So the ionic mobility increases when the oil viscosity decreases, thus when the temperature is raised, tanδ shows a remarkably increase.

However, as explained in 2.3.1, when the ion velocity increases to a certain value, Garton effect will appear in the insulation. Thus, when the temperature increases until the ion motion distance becomes smaller than the space in the paper pores, tanδ exhibits a decrease with electrical field intensity due to Garton effect.

2.4 Insulation aging

During service life, each cable system is exposed to aging caused by electrical, thermal mechanical and environmental stresses. The effect of insulation aging is decreasing the dielectric strength of insulating material. Aging is permanent and irreversible. In particular, old cable systems with impregnated paper insulation are very sensitive to any kind of overstressing. In the next paragraphs, two main ways of oil-impregnated paper aging are discussed: electrical and thermal aging. [15]

2.4.1 Electrical aging

Electric aging is referred mainly to the electrical overstressing of the insulation. The process of electrical aging is:

1) When having impurities and contaminations in insulation, Partial Discharges (PD) in the insulation creates "gas spots" and tracking in the insulation.
2) The gases arisen due to PD discharges make further deterioration of cellulose bonds and carbonizing but the gasses will also decrease PD inception voltage permanently.
3) Further deterioration due to arcing in spots leads to electrical treeing activity. Electrical treeing is a complex mechanism which results in creating channels and branches that can be created on the surface or within a dielectric material. This process will result in creating a conductive path and lead to the failure of the dielectric. Electrical treeing is a matter of weeks to several years [7].

2.4.2 Thermal aging

Thermal aging in impregnated paper is mainly to decomposition of paper structure [9]. The process of thermal aging is:

1) Temperature of insulation may be exceeded due to overloading of a cable or thermal instability, when cable insulation is not able to dissipate thermal energy produced in the conductor.

2) Because of elevated temperature, cellulose chains in the paper break and this produces H_2O, CO_2, and CO. In inhomogeneous areas the electrical field is locally enhanced, and this leads to further deterioration.
3) Water is the most dangerous byproduct because it is a conductive liquid. When water fills cracks in the paper, it results in higher conductivity in the region of the cracks but also provides faster ionization in this area.
4) Beside the breaking of cellulose chains, it is also due to local partial discharge activities and ionization processes that local overheating of paper is produced.
5) Thermal aging of paper insulation is also responsible for gas evaporation in particular aging stages. Besides CO_2 and CO, hydrogen, methane, ethane and ethylene are produced. Strong overheating of paper will result in the occurrence of CO and CO_2 where the CO/CO_2 ratio depends on temperature.
6) Overheating of oil produces ethylene C_2H_4 and arcing produces acetylene C_2H_2. Water and gases can exist in two forms in oil: bubbles or dissolved. When water is dissolved in oil, it contributes to the conductivity of insulation. On the other hand, when water and gases create bubbles, it results in partial discharge activity and further aging. This is a good example of a multifactor aging mechanism leading to a decrease of dielectric strength of insulation.[7]

3 Laboratory experiment

An experiment was conducted to research the influence of electrical intensity and temperature on oil-impregnated insulation and the relationship between dielectric loss and ageing.

3.1 Goal of the experiment

- The oil-impregnated papers are subjected to controlled aging.
- Analyze the behavior of dielectric loss value of oil-impregnated paper insulation under different electrical and thermal stress.
- Analyze the behavior of dielectric loss value at certain applied voltage in function of life consumption.
- Analyze the behavior of dielectric loss difference ($\Delta\tan\delta = \tan\delta(U2) - \tan\delta(U1)$, $U2>U1$) between two applied voltage in function of life consumption.
- Analyze the relative value ($\frac{\tan\delta(\mathrm{U2}) - \tan\delta(\mathrm{U1})}{\tan\delta(U1)}$) in function of applied voltage and life consumption.
- Fit a formula of insulation life consumption in function of relative tanδ value and voltage.

3.2 Test setup

The tanδ value of cables is often measured by means of Schering bridge. In the Schering bridge the cable insulation is regarded as an equivalent parallel circuit, consisting of a capacitance in parallel with a resistance. The basic Schering bridge circuit is depicted in Figure 3.1. When the bridged is balanced, the voltage across the null detector is zero. This can by achieved by fulfilling the requirement:

$$Z_3 Z_s = Z Z_4 \quad (11)$$

The dielectric loss value can be obtained as:

$$\tan\delta = \omega R_4 C_4 \quad (12)$$

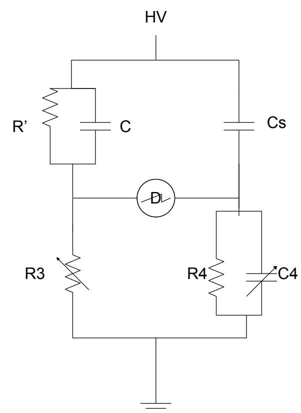


Figure 3.1 Basic Schering bridge circuit

Where:

C – capacitance of a sample

R’ – loss resistance of a sample

Cs – standard, loss free capacitor

R_3, R_4, C_4 – elements for balance adjustment

Figure 3.2, shows the test setup for dielectric loss measurement. The figure in the left shows the laboratory test setup of Schering bridge. The test setup consists of adjustable voltage source, step-up transformer, standard capacitor and the electrodes between which the sample is put into. The figure on the right side is a null detector and console for R_4 and C_4 adjustment.

Figure 3.2 Test setup for dielectric loss measurement

The samples are placed between the two electrodes. The normal configuration setup has two circular electrodes and a ring electrode around the low voltage electrode. Guard electrode eliminates surface leakage current which can affect the loss factor measurement. The set of these electrodes are placed in one of the arms of Schering bridge. In Figure 3.3, the electrodes are depicted.

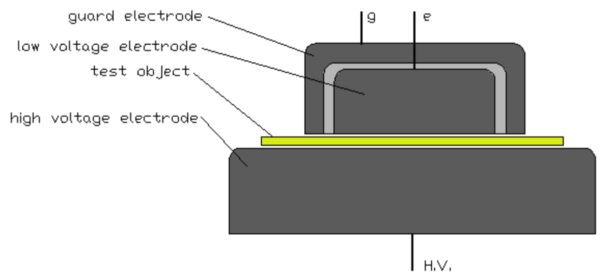


Figure 3.3 Cross-section of the electrodes

3.3 Test object

The test object is oil-impregnated paper insulation. To prepare the test object, the non-impregnated paper, which was delivered from a cable factory, was dried in a 70°C vacuum oven for 48 hours. The aim of drying in a vacuum was to remove the residual moisture bounded within the paper fibers. Applying a vacuum to this process allowed a lower temperature of drying, in order not to deteriorate the structure of the paper. The second step was to put the paper in dry and degassed oil “Shell Diala b”. The procedure of drying the oil was the same as in the case of paper. The last step was to immerse the paper in oil and subject to further drying for another 24 hours.

The samples of the test object, the oil-impregnated paper was subjected to accelerated thermal aging. A temperature of 110°C was chosen. Recalculating, the life consumption reaches 100% in 225 days when subjected to the accelerated thermal aging in a temperature of 110°C. The time necessary for accelerated aging was recalculated with Arrhenius Model.

For the on-site diagnostics, it is important to know the level of testing voltage. During previous research, samples taken from gas pressurized cable were investigated. The location of the samples is presented on the figure 3.4. The samples prepared in the laboratory and subjected to accelerated aging were of similar thickness to the sample II taken from the cable. Cross-section of the cable and location of the samples are shown in figure 3.4. Thus it is possible to obtain the per unit value of the voltage for samples measured in the test setup, which are relative to the real operation of the cable. The voltage of the samples can be calculated by using the relation between electrical field intensity and voltage of “sample II”.

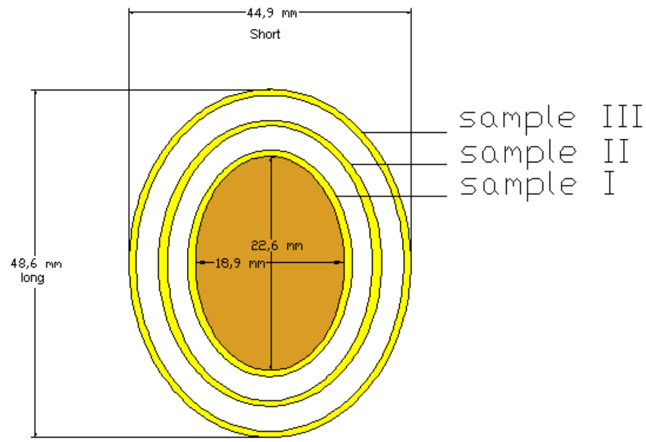


Figure 3.4 Samples locations [12]

For sample II, the relation between electrical field intensity applied on the paper insulation and cable voltage is:

$$E = \frac{U}{x \cdot \ln \frac{R}{r}} \quad (13)$$

Where:

U – cable voltage (nominal voltage is 115kV)

x – location of sample from paper layer (about 19mm for sample II-medium layer of insulation)

R – radius of the outer insulator (23mm)

r – radius of conductor (10mm)

3.4 Test results

The tests last for 225 days, and 40 samples are tested. The 40 samples are tested at different days between the 3rd day and the 218th day. Thus the 40 samples represent the 40 different percentage of life consumption of oil-impregnated paper insulation between 1% and 97% life consumption.

During testing, both electrical and thermal stress was changed. The values of sample temperature during testing were as follows: 25°C, 35°C, 50°C, 65°C and 80°C. The temperature of 25°C was the lowest possible to obtain as it was ambient temperature. The maximal permissible temperature of cable is 60°C, the behavior was also observed at higher temperatures to investigate thermal stability of insulation. At each temperature the dielectric losses of the samples were measured by changing electrical field intensities from 0.7kV/mm to 6.7kV/mm.

In figure 3.5, the influences of electrical field intensity, temperature and aging on dielectric loss value are shown.

a. Electrical field intensity and temperature influences:

Non-aged insulation:

- Dielectric loss value increases with electrical field intensity due to polarization.
- At constant electrical field intensity, dielectric loss value decreases with temperature from 25°C to 50°C due to free radicals.
- At constant electrical field intensity, dielectric loss value increases with temperature from 50°C to 80°C due to oil viscosity decrease.

Aged insulation:

- The tanδ value increases with electrical field intensity at low temperature (25°C to 65°C) due to polarization.
- The tanδ value decreases with electrical field intensity at low temperature (80°C) due to Garton effect.

- At constant electrical field intensity, dielectric loss value increases with temperature due to oil viscosity decrease.

b. Aging influences:

- At constant temperature and electrical field intensity, the tanδ value increases with life consumption.
- The increase of the tanδ value with electrical field intensity becomes larger at constant temperature.
- Garton effect starts to happen at 80°C. The decrease of the tanδ value becomes larger.
- The effect of free radicals can be ignored.
- The effect of oil viscosity decrease plays a major role.
- The increase of the tanδ value with temperature at constant electrical field intensity becomes larger.

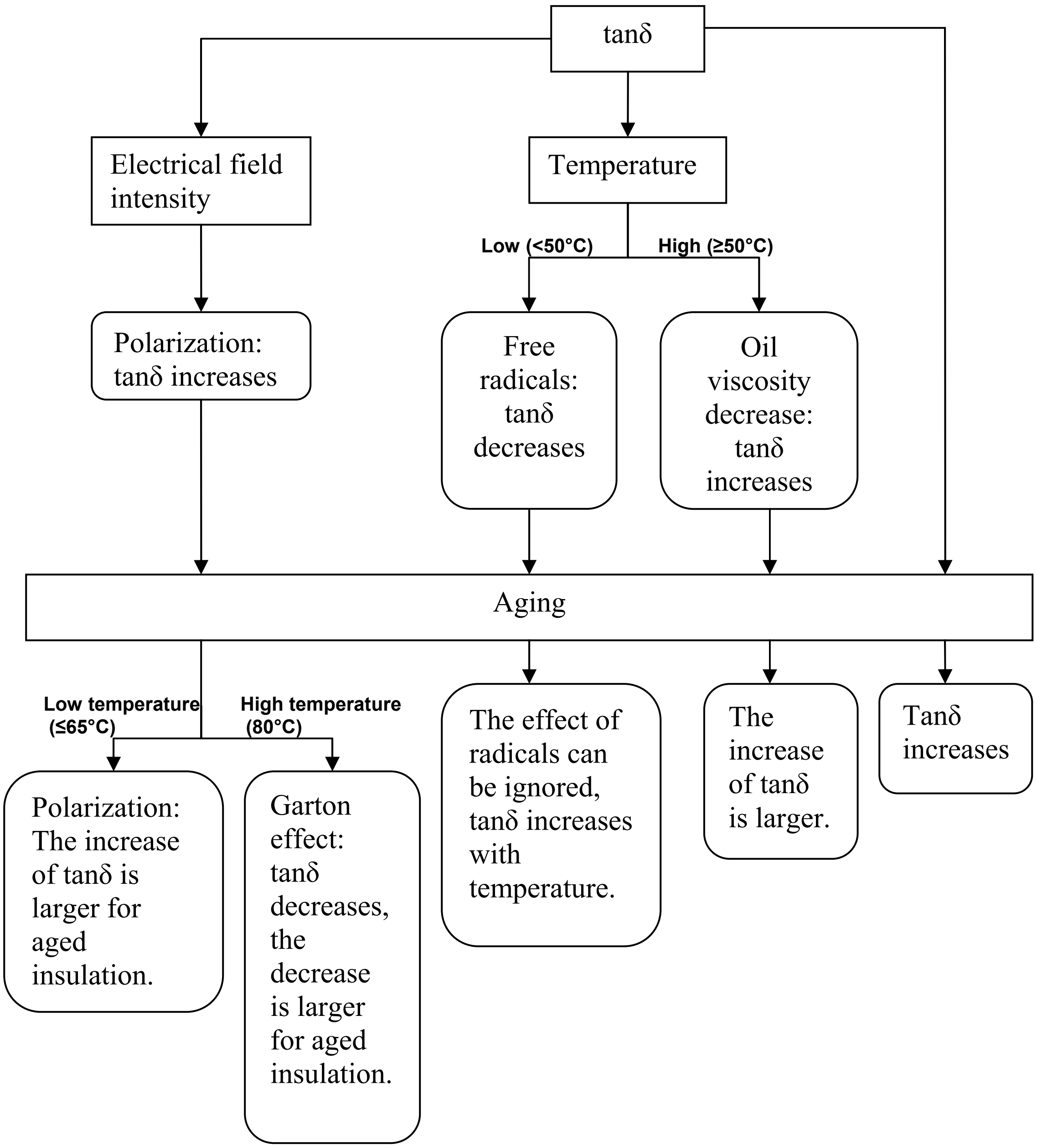


Figure 3.5 influences of electrical field intensity, temperature and aging on tanδ value

3.4.1 Results of influence of electrical field intensity on impregnated paper insulation

1. Influence of electrical field intensity on impregnated paper insulation at low temperature.

The on-site testing can only be performed at low temperature, so in the investigation of tanδ value in function of electrical field intensity, the temperature applied on the insulation is 25°C.

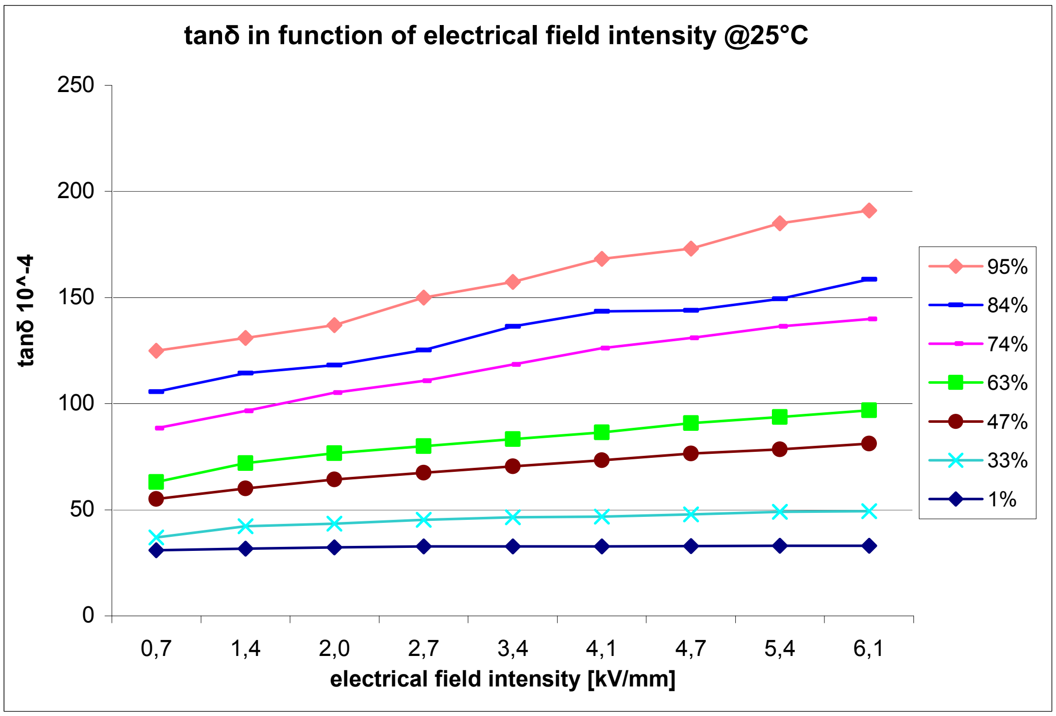


Figure 3.6 tanδ value in function of electrical field intensity at 25°C for samples characterized by different life consumption

Figure 3.6 shows dielectric loss value in function of electrical field intensity at temperature 25°C. The different color lines indicate different percentage of life consumption of the insulation.

- At constant electrical field intensity, the tanδ increases for samples characterized by higher life consumption. For example, at 0.7kV/mm electrical field intensity, the tanδ

$^{-4}$ and the tanδ value of 95% life consumption is $125*10^{-4}$, the increase is $94.4*10^{-4}$.

- Moreover, the tanδ value increases with electrical field intensity. For the samples characterized by higher life consumption (higher degradation) increase becomes higher than for samples characterized by lower life consumption. For example, between 0.7kV/mm and 6.1kV/mm, for 1% life consumption insulation, the Δtanδ value is $2.2*10^{-4}$ and for 95% life consumption insulation, the Δtanδ value is $66*10^{-4}$.

The reasons of the influence of electrical field intensity on paper insulation can be deducted from porous structure of paper, as described in chapter two: the conduction in impregnated paper can be described according to the motion of ions in oil. When an electric field is applied, increasing applied field intensity enhances the ionic motion in the oil. The tanδ value exhibits an increase with applied voltage. This is caused by the fact that a rising applied field increasingly segregates the oppositely charged ions, which can be explained by atomic induced polarization. Aged paper insulation contains more pores and impurities, which increases tanδ dependence on electrical field.

At temperature 35°C, 50°C and 65°C, the dielectric loss behaviors in function of electrical field intensity are similar, only the tanδ values are higher than these at 25°C, the influence of temperature on dielectric loss behavior is discussed later in this chapter.

2. Influence of electrical field intensity on impregnated paper insulation at high temperature

Figure 3.7 shows the dielectric loss value in function of electrical field intensity at a temperature of 80°C. The different color lines indicate different percentage of life consumption of the insulation, the life consumption are chosen from between 33% to 95%, due to the fact that Garton effect on the insulation at a temperature of 80°C starts at 33% life consumption.

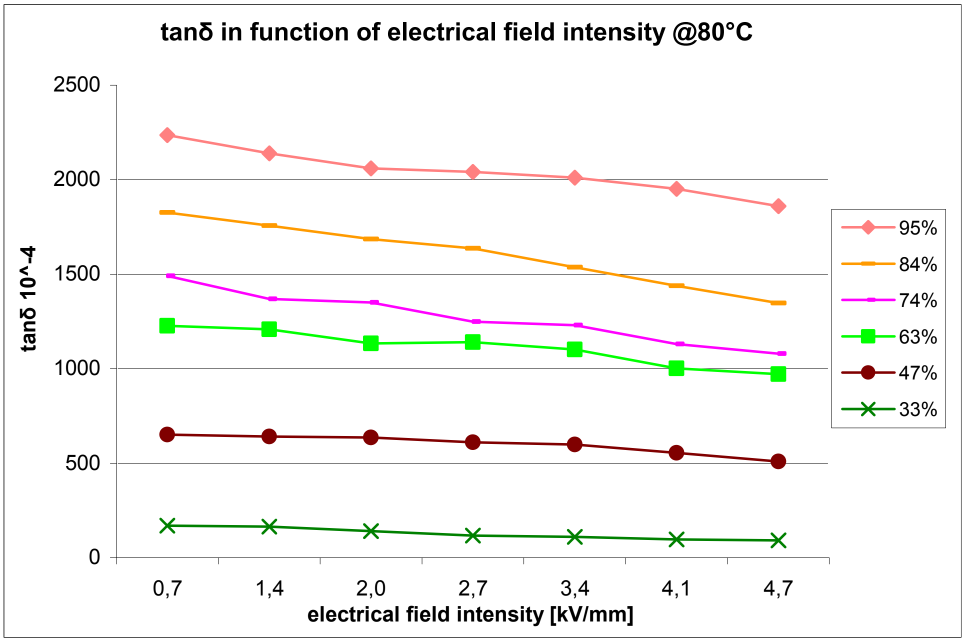


Figure 3.7 tanδ value in function of electrical field intensity at 80°C and different life consumption

- At a constant electrical field intensity, the tanδ increases for samples characterized by higher life consumption. At 0.7kV/mm electrical field intensity, 33% life consumption insulation has $170*10^{-4}$ tanδ value and 95% life consumption insulation has $2236*10^{-4}$ tanδ value, the increase is $1066*10^{-4}$.
- The tanδ value decreases with electrical field intensity after the samples got 33% life consumption. For the samples characterized by higher life consumption (higher degradation) decrease becomes higher than for samples characterized by lower life consumption. For example, between 0.7kV/mm and 4.7kV/mm, for 33% life consumption insulation, the Δtanδ value is $85.4*10^{-4}$ and for 95% life consumption insulation, the Δtanδ value is $376*10^{-4}$.

This is due to Garton effect, which can be explained as follows: when the paper is subjected to high stress (electric field intensity and temperature), an increase of the electric field intensity on the paper increases ionic motion in pores of the paper. When the oil space is less than the ionic motion distance, there will be collisions of ions on the boundary of the paper fiber, and therefore the dielectric losses start to decrease. In aged paper, there is more moisture and there are more impurities, which increases the Garton effect on the paper insulation.

3.4.2 Results of influence of temperature on impregnated paper insulation

Here the electrical field intensity value is chosen 0.7kV/mm, because the temperature control is more stable and the tanδ values measured at high temperatures are more accurate at low electrical field intensity.

1. The tanδ value in function of temperature at constant electrical field intensity when insulation life consumption is lower than 30%.

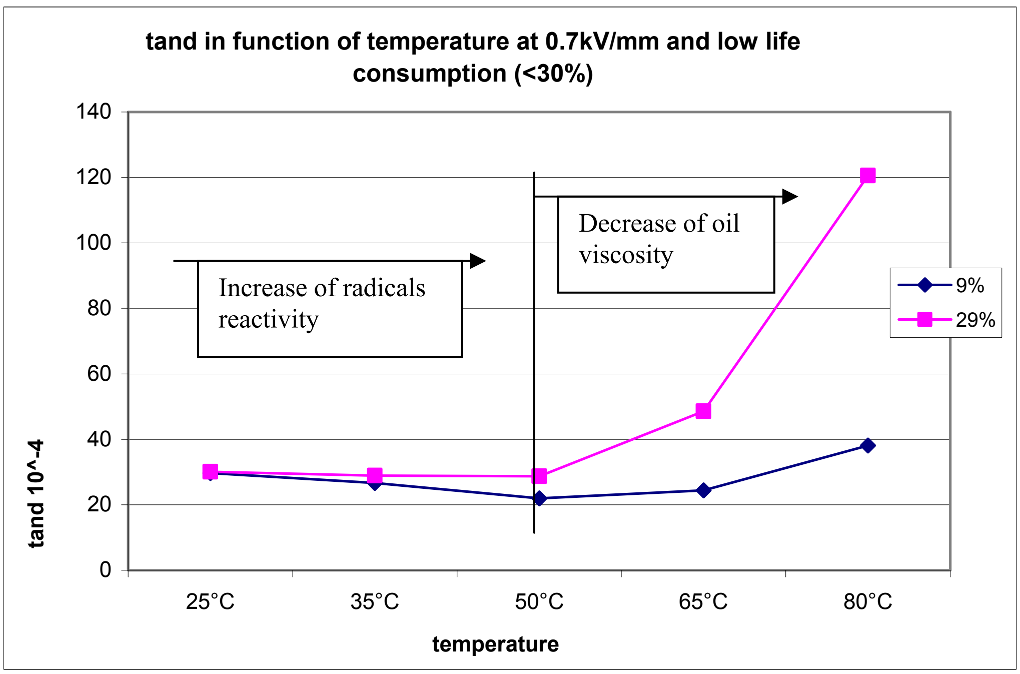


Figure 3.8 tanδ in function of temperature at 0,7kV/mm electrical field intensity and low life consumption (<30%)

Figure 3.8 shows the dielectric losses behavior of low life consumption insulation in function of temperature at constant electrical field intensity. Different color lines indicate different life consumption.

- When the temperature is lower than 50°C, the tanδ value decreases with temperature. For insulation at 9% life consumption, the tanδ value at 25°C is $29.7*10^{-4}$ and the tanδ value at 50°C is $22*10^{-4}$.
- For the samples characterized by higher life consumption (higher degradation) decrease becomes lower than for samples characterized by lower life consumption. Between 25°C and 50°C, for insulation at 9% life consumption, the tanδ value decrease is $7.7*10^{-4}$ and for 29% life consumption insulation, the tanδ value decrease is $1.4*10^{-4}$.
- When the temperature is higher than 50°C, the tanδ value increases with temperature. For the insulation at 9% life consumption, the tanδ value at 50°C is $22*10^{-4}$ and the tanδ value at 80°C is $38.1*10^{-4}$.
- For the samples characterized by higher life consumption (higher degradation) increase becomes higher than for samples characterized by lower life consumption. Between 50°C and 80°C, the tanδ value increase of 9% life consumption insulation is $16.1*10^{-4}$ and the tanδ value increase of 29% life consumption insulation is $91.9*10^{-4}$.

The influences of temperature on oil-impregnated paper insulation (life consumption <30%) can be explained by taking into account that:

1) The fact of the tanδ values decreasing below 50°C at 9% and 29% life consumption can be explained by presence of special ionized particles in impregnating medium – free radicals [14]. Free radicals are particles with impaired electron on last orbital; they can be electrically conductive and contribute to dielectric losses. Their reactivity increases with temperature, and they react with other conductive particles, thus the number of conductive particles decreases.
2) When the temperature is higher than 50°C however, the impregnating medium loses its viscosity. When oil viscosity becomes lower, the ionic motion in the oil becomes higher, this causes the increase of dielectric loss.
3) When the insulation has a higher degradation, the effect of oil viscosity decreases with temperature. Thus the free radicals effect has a weaker effect.

2. The tanδ value in function of temperature at constant electrical field intensity when insulation life consumption is higher than 30%.

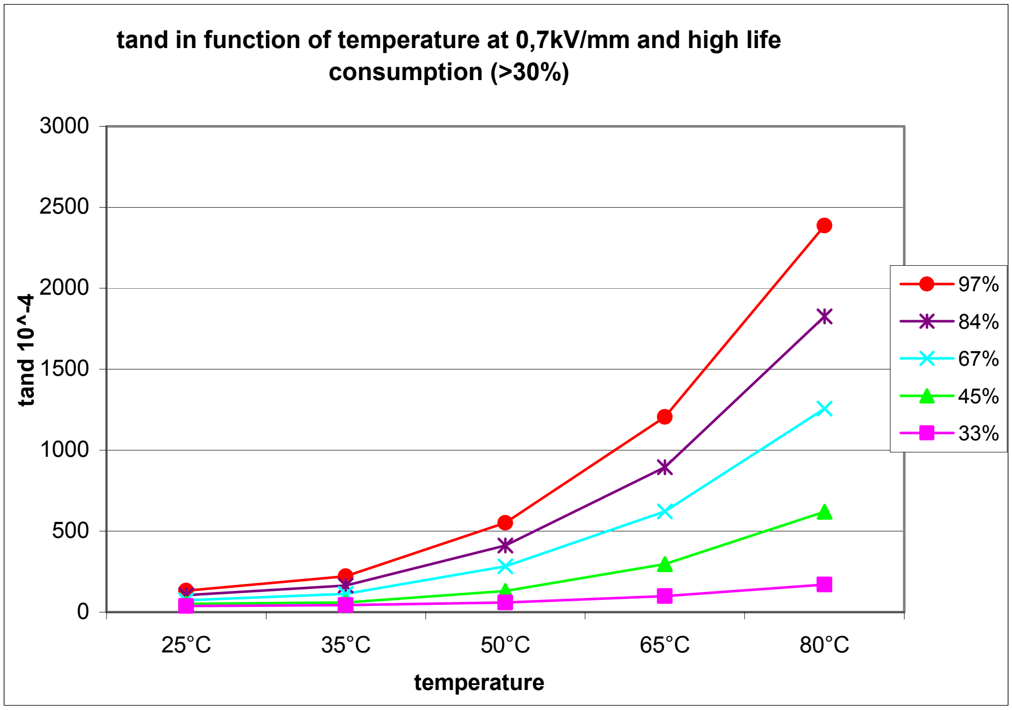


Figure 3.9 tanδ in function of temperature at 4,7kV/mm electrical field intensity and high life consumption (>30%)

Figure 3.9 shows at constant electrical field intensity, the behavior of dielectric losses in function of temperature of high life consumption insulation. Different color lines indicate different life consumption.

- At constant temperature, the tanδ increases for samples characterized by higher life consumption. At 25°, the tanδ value of 33% life consumption insulation is $37*10^{-4}$ and the tanδ value of 97% life consumption insulation is $132*10^{-4}$, the increase is $95*10^{-4}$.
- The tanδ value increases significantly with temperature. For the samples characterized by higher life consumption (higher degradation) increase becomes higher than for samples characterized by lower life consumption. Between 25°C and 80°C, for 33% life consumption insulation, the tanδ value difference is $133*10^{-4}$ and for 97% life consumption insulation, the tanδ value increase is $2255*10^{-4}$.

The reasons of the influence of temperature on oil-impregnated paper insulation (life consumption>30%) are:

1) For aged insulation, the effect of oil viscosity decrease with temperature plays the major role in the influence. When oil viscosity becomes lower, the ionic motion in the oil becomes higher; this causes the increase of dielectric loss.
2) When the aged insulation got higher degradation, there are more impurities which increase the oil conductivities even higher with the temperature. Thus the increase of dielectric loss becomes higher.

3.5 Data analysis

The data found in the experiment are analyzed to establish the relation between life consumption and the tanδ value at different applied voltage. This relation is needed to be able to build a model for diagnosing life consumption and future life estimation of oil-impregnated paper insulated cable.

In this analysis, the samples are subjected to accelerated aging from 1% to 100%. The electrical field intensity applied to the insulation samples during laboratory testing is transferred to per unit voltage value applied to the cable using the equation in chapter 3.2.

1. The relation between dielectric loss value ,life consumption and applied voltage

Figure 3.10 shows dielectric loss value in function of life consumption; different colors represent different applied voltage. The Uo means the nominal voltage of the cable. The dielectric loss value increases exponentially with life consumption for a particular (constant value of) voltage applied. Moreover the increase is larger when the voltage applied to the insulation is larger.

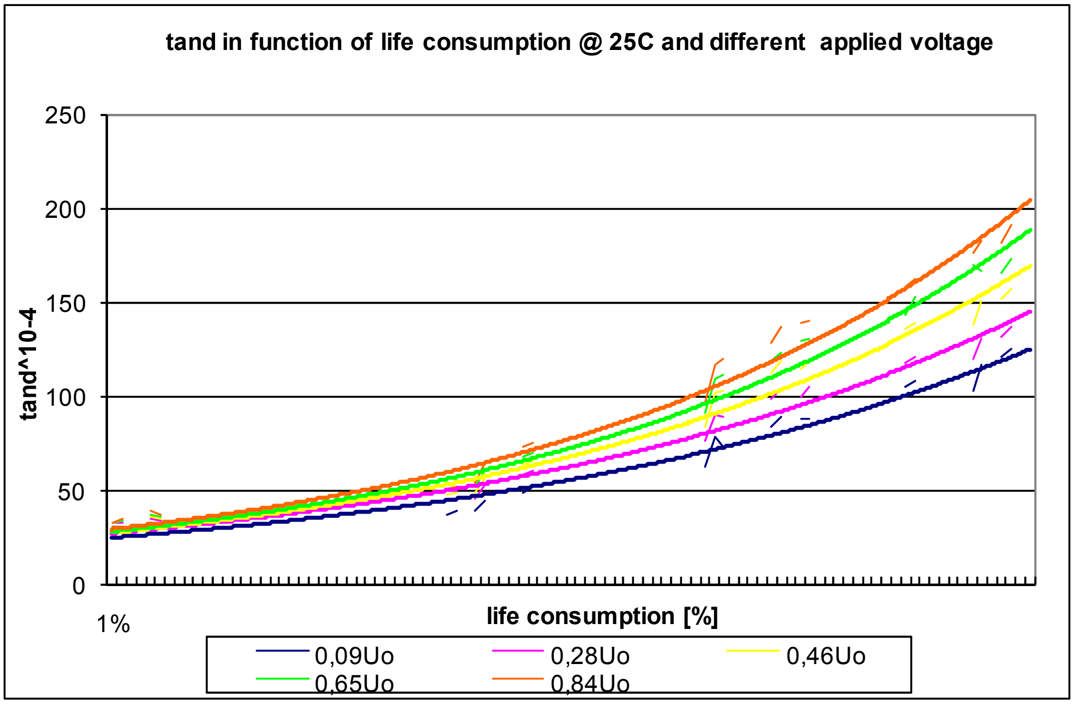


Figure 3.10 tanδ value in function of life consumption at 25°C and different life consumption

2. Relation between Δtanδ, voltage and life consumption

During the test, the highest electrical field intensity applied on the samples is 6.1kV/mm, and the lowest one is 0.7kV/mm. When the electrical field intensity values are recalculated as voltage value applied on cable, the two values are 0.84Uo and 0.09Uo. So in the Δtanδ value analysis, the voltages are chosen 0.09Uo and 0.84Uo.

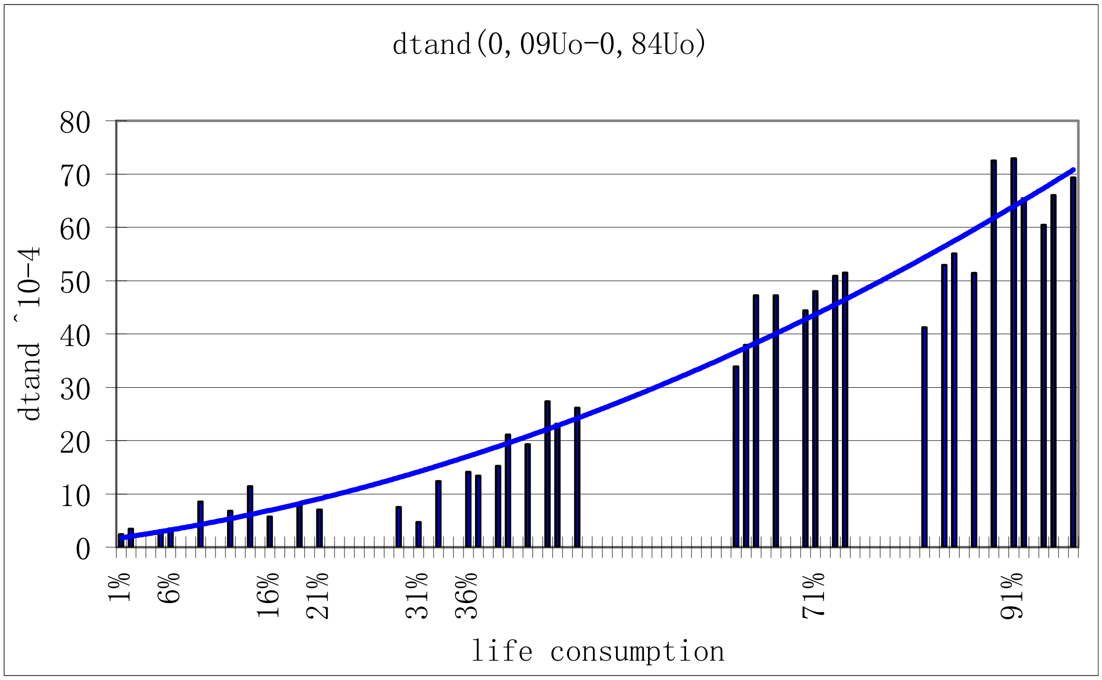


Figure 3.11 ∆tanδ between 0.09Uo and 0.84Uo in function of life consumption at 25°C

Figure 3.11 shows ∆tanδ in function of life consumption, ∆tanδ is the dielectric loss value difference between 0.09Uo and 0.84Uo applied voltage. Here, the ∆tanδ increases exponentially with life consumption, but the steepness of the increase is smaller than in the case of tanδ in function of life consumption. For ∆tanδ between other voltage differences the curve is similar.

3. Extrapolation of the relation between tanδ value and applied voltage

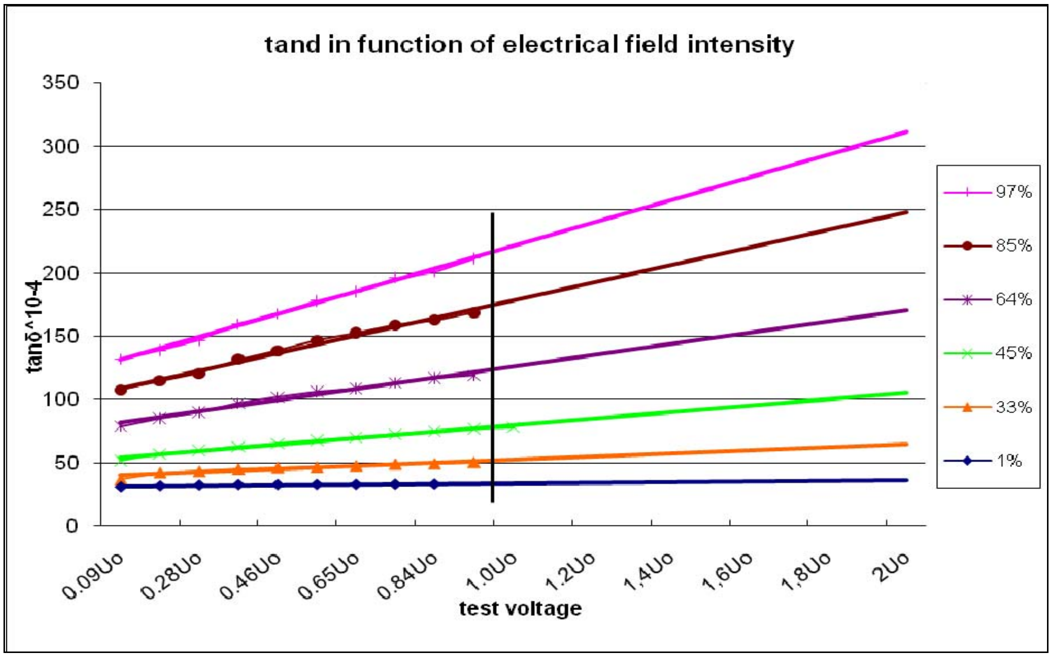


Figure 3.12 tanδ in function of applied voltage at different life consumption

Figure 3.12 shows the relation between dielectric loss value and applied voltage on the cable, different colors represent different life consumption. Due to the fact that tanδ depends linearly on applied voltage, extrapolation for voltage higher than Uo was made.

4. Relative tanδ in function of voltage and life consumption.

From the first two results, it is already known that Δtanδ and tanδ both change exponentially with life consumption. If Δtanδ is divided by tanδ, the relative tanδ value will change linearly with life consumption.

$$relative\_\tan\delta = \frac{\tan\delta(U2) - \tan\delta(U1)}{\tan\delta(U1)} \quad (14)$$

The reason for choosing relative tanδ value instead of Δtanδ is that the tanδ value in the lab is different from the real cable tanδ value, but for relative tanδ value, the measurement value and real cable value are similar.

1) Comparison of the on-site diagnose and laboratory relative tanδ value

In Figure 3.12, cable on-site diagnostic relative tanδ value and laboratorial relative tanδ value are compared. The values are quite similar, and they both change linearly. The blue color line indicates the on-site diagnostic relative tanδ value in function of applied voltage. The test voltages for on-site diagnostic are from 40kV to 150kV, which in per unit value are 0.3Uo to 1.2Uo. But for the laboratory relative tanδ value, the applied voltages are from 0.09 to 0.84Uo. So for the convenience of the comparison, the applied voltages are chosen from 0.3Uo to 0.8Uo.

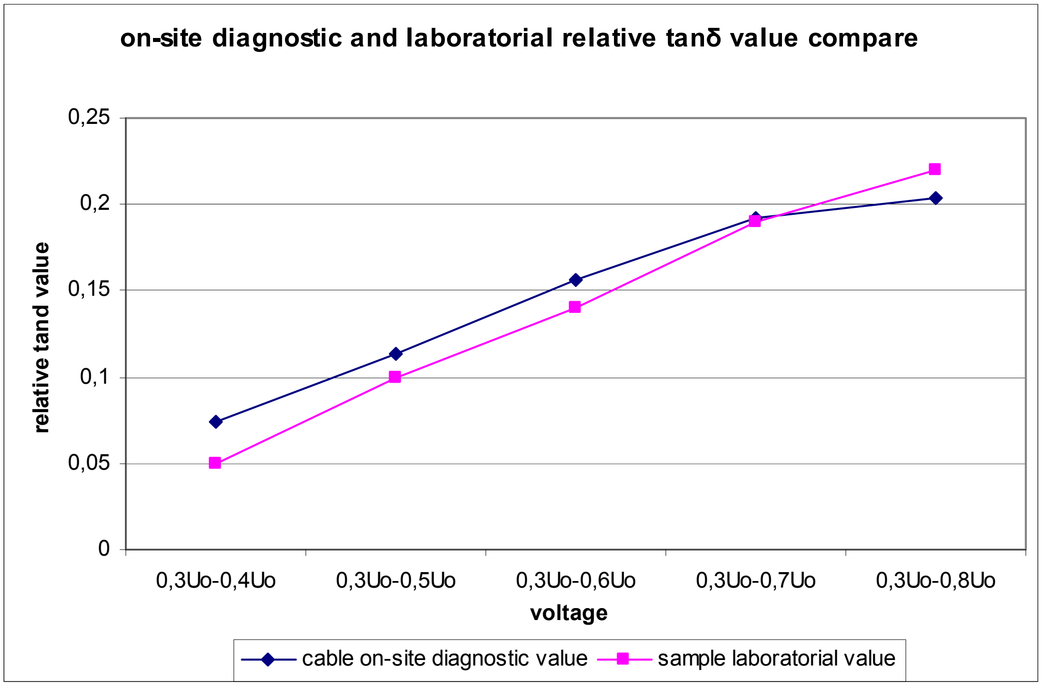


Figure 3.13 cable on-site diagnostic and laboratorial relative tanδ value compare

In Figure 3.13, the pink line indicates the laboratory relative tanδ value from between 0.3Uo and 0.4Uo to 0.3Uo to 0.8Uo, the life consumption of the insulation is 47%. It can be seen that the values of on-site diagnose data and laboratory data are very similar, and the linear relations with voltage difference are almost the same. Thus the relative tanδ value can be used for the life consumption diagnose.

2) The relation between relative tanδ value and voltage difference

Table 3.1 shows the relative tanδ value, when U1 is 0.19Uo, and Figure 3.12 shows the relation among relative tanδ (U1=0.19Uo), voltage difference and life consumption.

voltage / Life consumption	0,19Uo-0,28Uo	0,19Uo-0,37Uo	0,19Uo-0,46UO	0,19Uo-0,56UO	0,18Uo-0,65Uo	0,19Uo-0,74Uo	0,19Uo-0,84Uo
2%	0,02	0,03	0,03	0,03	0,03	0,05	0,06
21%	0,03	0,06	0,07	0,07	0,09	0,12	0,15
42%	0,05	0,09	0,13	0,16	0,20	0,24	0,28
64%	0,06	0,14	0,20	0,24	0,28	0,33	0,37
97%	0,06	0,15	0,21	0,28	0,33	0,41	0,45

Table 3.1 relative tanδ(U1=0.19Uo) at different voltage difference and different life consumption

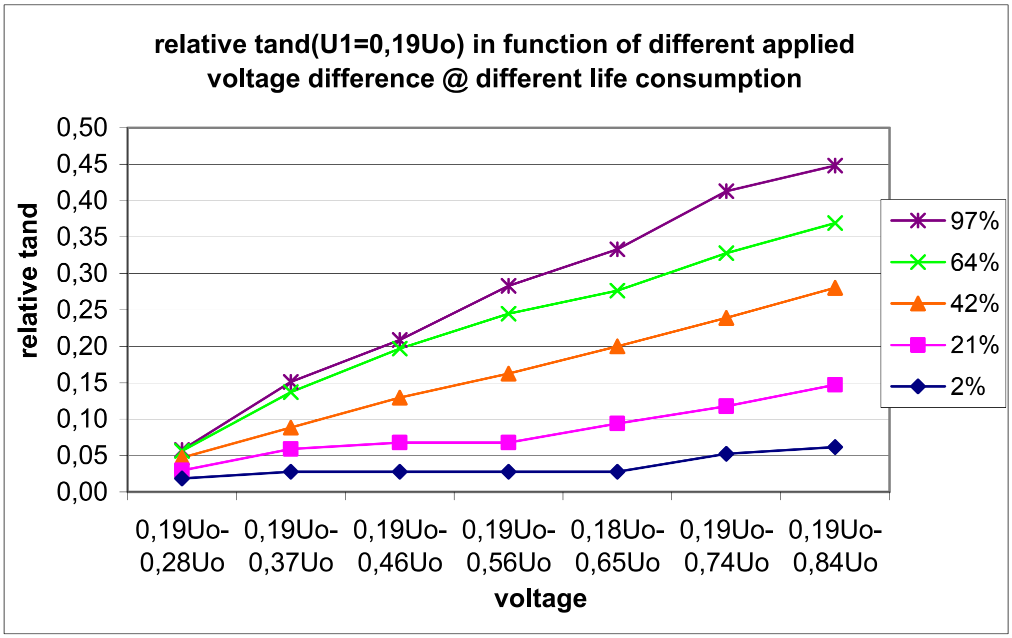


Figure 3.14 relative tanδ(U1=0.19Uo) in function of voltage difference at different life consumption

In Figure 3.14, it can be seen that the relative tanδ value increases linearly with voltage difference. For more degraded paper insulation, the increase is bigger.

3) The relation between relative tanδ value and lower voltage U1

Table 3.2 shows the different life consumption relative tanδ values when voltage difference is kept the same, but the lower voltage changes. Figure 5 shows the relation among relative tanδ value, life consumption and different low voltage (U1).

voltage / Life consumption	0,09Uo-0,46Uo	0,28Uo-0,56Uo	0,37Uo-0,65Uo	0,37Uo-0,74Uo	0,46Uo-0,84Uo
1%	0,06	0,03	0,02	0,01	0,01
29%	0,11	0,07	0,06	0,05	0,04
42%	0,25	0,16	0,15	0,14	0,13
64%	0,29	0,24	0,21	0,17	0,14
84%	0,29	0,26	0,22	0,19	0,16

Table 3.2 relative tanδ in function of different lower voltage, same voltage difference and different life consumption

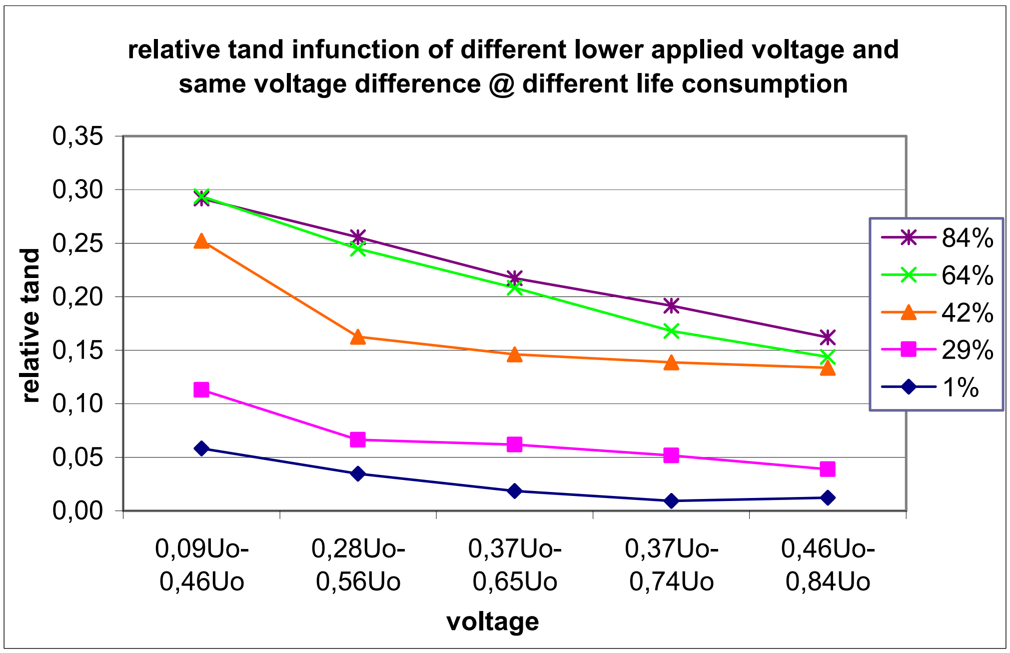


Figure 3.15 relative tanδ in function of different lower voltage and same voltage difference at different life consumption

In Figure 3.15, it can be seen that the relative tanδ value decreases with voltage intensity (U1). For higher life consumption the decrease is bigger.

So by analyzing all the data of relative tanδ in function of applied voltage and life consumption, it can be concluded that:

- Relative tanδ value changes linearly with the voltage difference and the lower voltage.
- The steepness of the linear relation between relative tanδ and voltage changes with the life consumption of the paper insulation.

Thus by using these results, a formula can be fitted to calculate life consumption by relative tanδ value:

$$ILC[\%] = 10 * \frac{0.09}{U_2 - U_1} * 1.1^{\frac{U_1}{0.09}} * \frac{\tan\delta(U_2) - \tan\delta(U_1)}{\tan\delta(U_1)} \quad (15)$$

It can be seen that relative tanδ value has a linear relation with life consumption, and the steepness of the linear equation depends on the voltage difference and lower voltage U1. So by using this formula, inputting two different voltage U1 and U2 (U2>U1) and two tanδ value, the life consumption can be calculated.

4 Life consumption and future life estimation modeling

In this chapter, a model is established for diagnosing the life consumption and future life estimation of oil-impregnated paper insulated cable.

As introduced in chapter 3, the relative tanδ value changes linearly with voltage and life consumption. Thus, the relative tanδ value which is measured at low temperature during on-site diagnosis, is a useful tool to assess the life consumption of oil-impregnated paper insulation (Insulation Life Consumption ILC). A second method to diagnose the life consumption of the insulation is based on thermal aging and Arrhenius Law (Operational Life Consumption OLC). The future life estimation is based on both thermal aging and the result of life consumption calculated by relative tanδ value. The two calculations of life consumption should take different weights to be combined together.

Figure 4.1 shows the flow chart of the whole program. The first step, described in paragraph 4.1 is life consumption calculation, using both relative tanδ value and thermal aging. In paragraph 4.2 the second step is to combine the two results by giving different weight to the results. Finally the life consumption result and thermal aging theory are used to calculate future life estimation in paragraph 4.3.

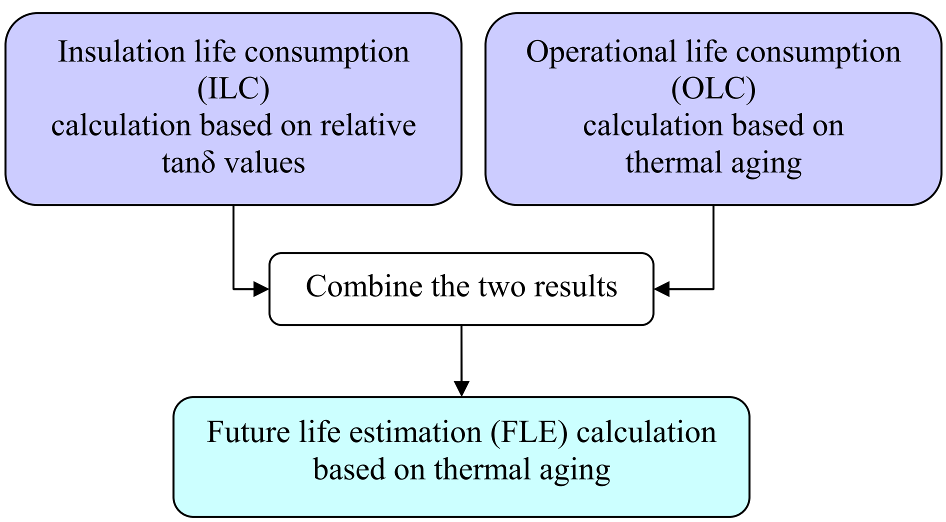


Figure 4.1 Flow chart of life consumption and future life estimation calculations

4.1 Life consumption calculation

4.1.1 Insulation life consumption calculation

From the data analysis in chapter 3, it can be seen that the relation between insulation life consumption and relative tanδ depends on the voltage difference and lower voltage value. So the fitting formula for calculating life consumption by relative tanδ value provided by data analysis is:

$$ILC[\%] = 10 * \frac{0.09}{U_2 - U_1} * 1.1^{\frac{U_1}{0.09}} * \frac{\tan\delta(U_2) - \tan\delta(U_1)}{\tan\delta(U_1)} \qquad (15)$$

Based on this formula, insulation life consumption (ILC) can be calculated by inputting two voltage values at which measurements were performed; U1 and U2, and two dielectric loss values, tanδ(U1) and tanδ(U2). In figure 4.2, the flowchart of program of insulation life consumption calculation by relative tanδ value is shown. Test value U1 and test voltage U2 are inputted into the insulation life consumption calculation formula. Values of tanδ(U1) and tanδ(U2) are inputted in the calculation of relative tanδ value, after that the result of relative tanδ value is inputted into the insulation life consumption calculation formula. The output is the percentage of insulation life consumption. In this program, when the ILC is lower then 10%, Δtanδ just has a very slight change, so the calculation can't show clear life consumption results under 10%.

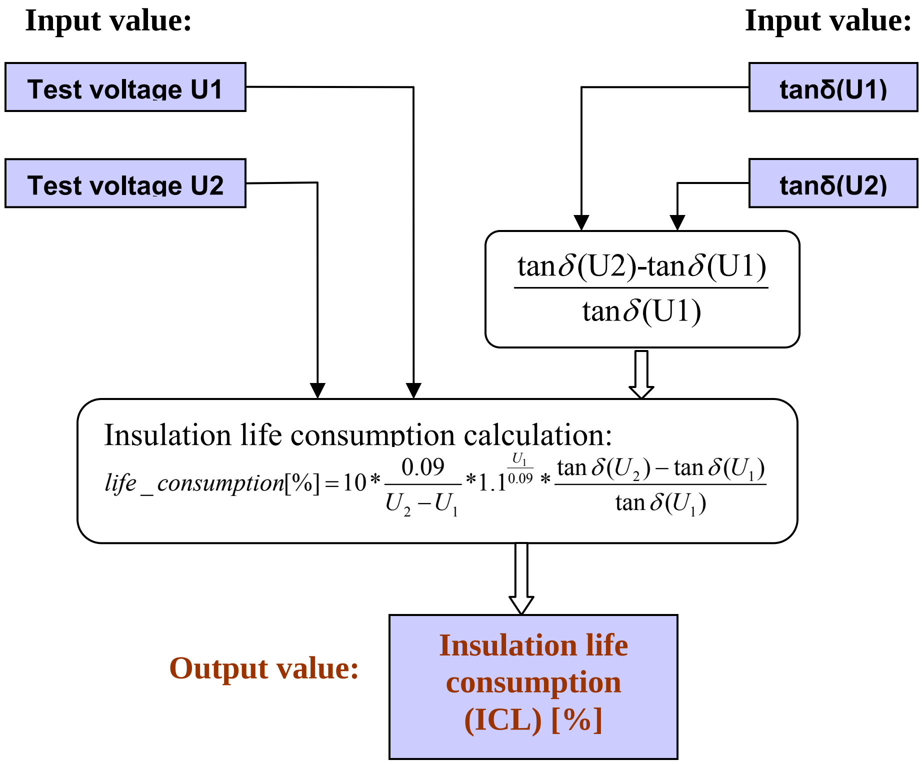


Figure 4.2 flow chart of ILC calculation by relative tanδ value

In figure 4.3, the interface of ILC calculation program in excel is shown. The upper row shows the two input voltage values, U1 and U2 in per unit value. The lower row shows the two input tanδ values, tanδ(U1) and tanδ(U2) and the output insulation life consumption value.

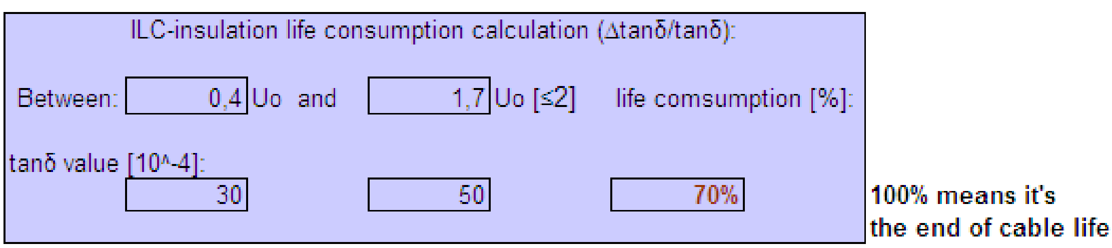


Figure 4.3 the interface of ILC calculation program

4.1.2 Operational life consumption calculation

The operational life consumption (OLC) calculated by past load is based on the Arrhenius law. Insulation degradation due to the load can be regarded as a thermal aging process. Arrhenius law describes the relation between temperature and degradation rate, which shows that the temperature has an exponential influence on the degradation rate of the insulation. The law of Monstsinger describes that at a certain temperature the degradation rate doubled. The formula of Monstsinger is shown below [4]:

$$D_{year} = D_{to} * 2^{(\frac{T_{conductor} - 15}{T_d})} \quad (5)$$

Where:

Dyear is yearly degradation

Dto is degradation rate at 15°C

Td is temperature difference to get double degradation

Tconductor is cable temperature

According the Monstsinger law, the parameters to calculate degradation rate by cable temperature are the temperature increase to obtain degradation (Td) and degradation rate at 15°C (Dto). For different kinds of insulation, the two parameters are different. In table 4.1, typical Dto and Td values of external gas-pressured mineral oil cable, external gas-pressured synthetic oil cable and paper insulated lead covered cable are shown[4].

Cable types	Td	Dto	Tmax
External gas-pressure mineral oil cable	13°C	1%	60°C
External gas-pressure synthetic oil cable	21°C	1%	85°C
Paper insulated lead covered (PILC) cable	6,5°C	0,5%	43°C

Table 4.1 Typical Dto and Td values of different types of cables

The cable temperature (Tconductor) can be calculated from load applied on the cable. The relation between cable temperature and load has been introduced in Chapter 1, the formula is shown below:

$$T_{conductor} = T_{ground} + (T_{\max} - T_{ground}) * (load\%)^2 \ (3)\ [7]$$

Tmax is the maximum operational temperature for the cable. The maximum temperature is different for different types of cable. Table 4.1 shows the maximum temperature for different types of cables.

Figure 4.4 shows the flow chart of operational life consumption calculated by past load. Percentage of load, ground temperature and cable maximum operational temperature are inputted into the cable temperature calculation. Then the result of cable temperature, Td and Dto values are inputted into the calculation of the yearly degradation of the cable. After that, the result of yearly degradation of the cable and cable age are inputted into the OLC calculation.

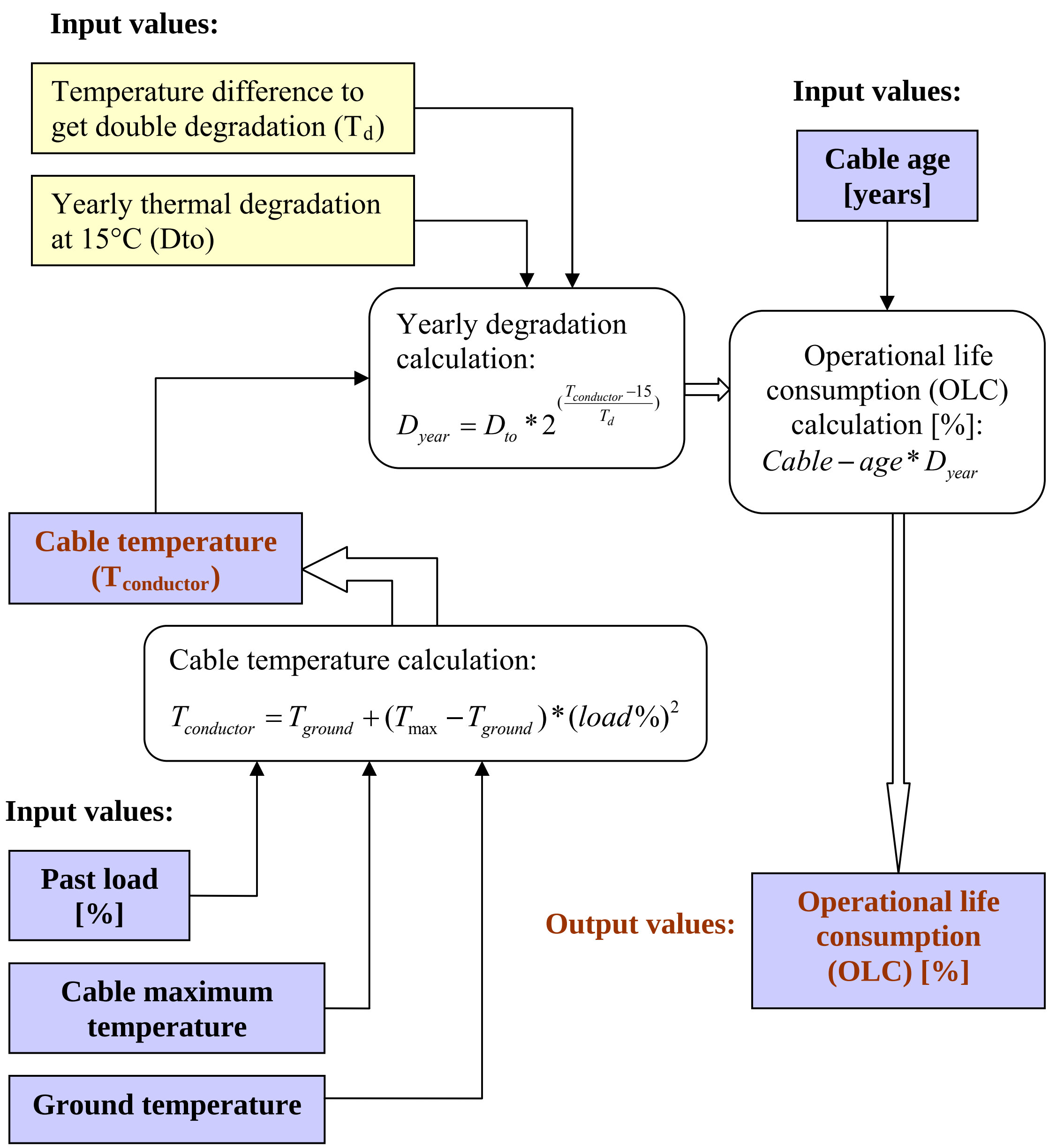
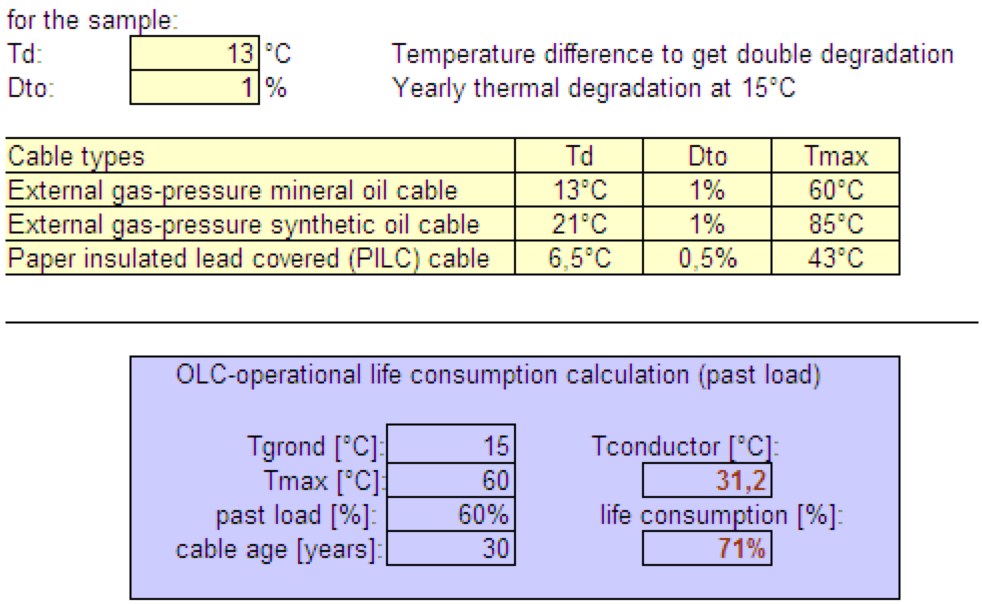


Figure 4.4 Flow chart of OLC calculation by past load

In Figure 4.5, the interface of operational life consumption calculation in excel is shown. Td and Dto are the input values. The values are based on the types of cable. The values of three different types of cable are shown in the figure. Below that, it is shown that when Tground, Tmax, percentage of past load and cable age are input values, the results are $T_{condutor}$ and operational life consumption.



Cable types	Td	Dto	Tmax
External gas-pressure mineral oil cable	13°C	1%	60°C
External gas-pressure synthetic oil cable	21°C	1%	85°C
Paper insulated lead covered (PILC) cable	6,5°C	0,5%	43°C

Figure 4.5 the interface of OLC calculation by past load

4.2 Total life consumption calculation

The total life consumption (TLC) calculation is based on the result of ILC and OLC. So first, the two results of life consumption calculated by different methods should be combined together. By combination of the two results total life consumption (TLC) is obtained. In figure 4.6, the two results of life consumption calculation are combined together using different weights for better accuracy. The phases U, V and W represent the three phases of a cable. During the life consumption calculation, the three phases are all taken into account. The ILC results of the three phases are compared, if the difference is smaller than 3%, ILC takes 50% weight, and OLC takes 50% weight; If the difference is larger than 3% and smaller than 5%, ILC takes 60% weight, and OLC takes 40% weight; If the difference is larger than 5%, ILC takes 70% weight, and OLC takes 30% weight. So the total life consumption value depends on the difference of ILC value between each phase.

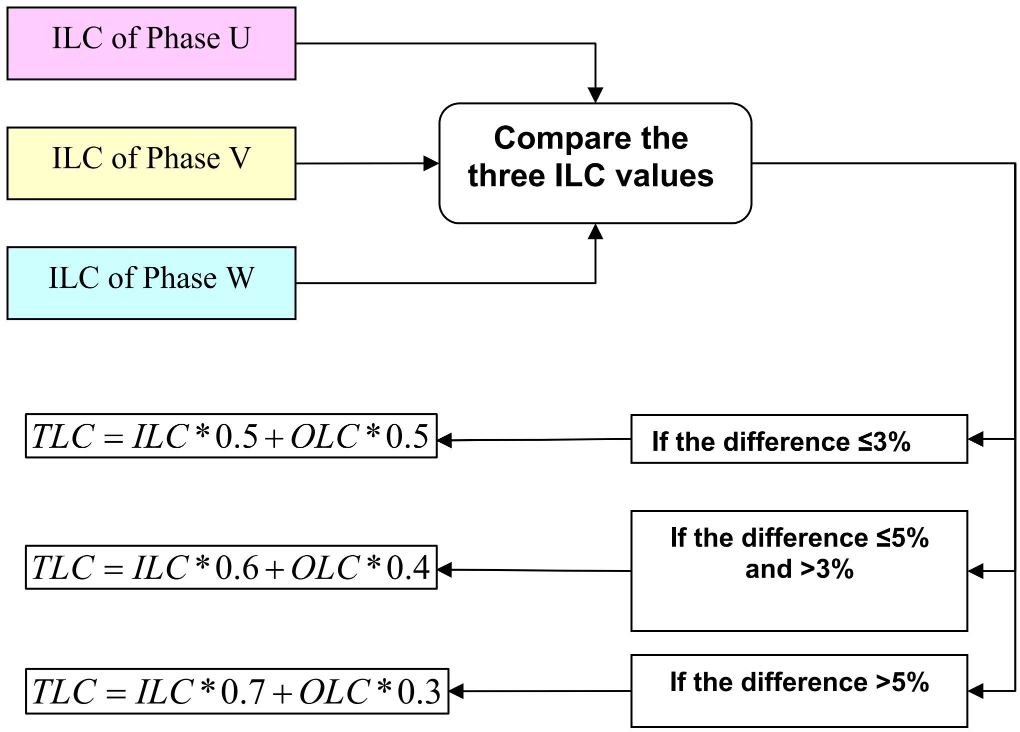


Figure 4.6 Flow chart of total life consumption (TLC) calculation

4.3 Future life estimation calculation

The calculation of future life estimation (FLE) is based on total life consumption and thermal aging. Figure 4.7 shows the flow chart of calculation of future life estimation. Until the calculation of yearly degradation, the procedure is similar to the life consumption calculation by past load, only now the future applied load should be taken instead of past load value. After that, the result of total life consumption is inputted. The output value, future life estimation, is based on the percentage of total life consumption and yearly degradation.

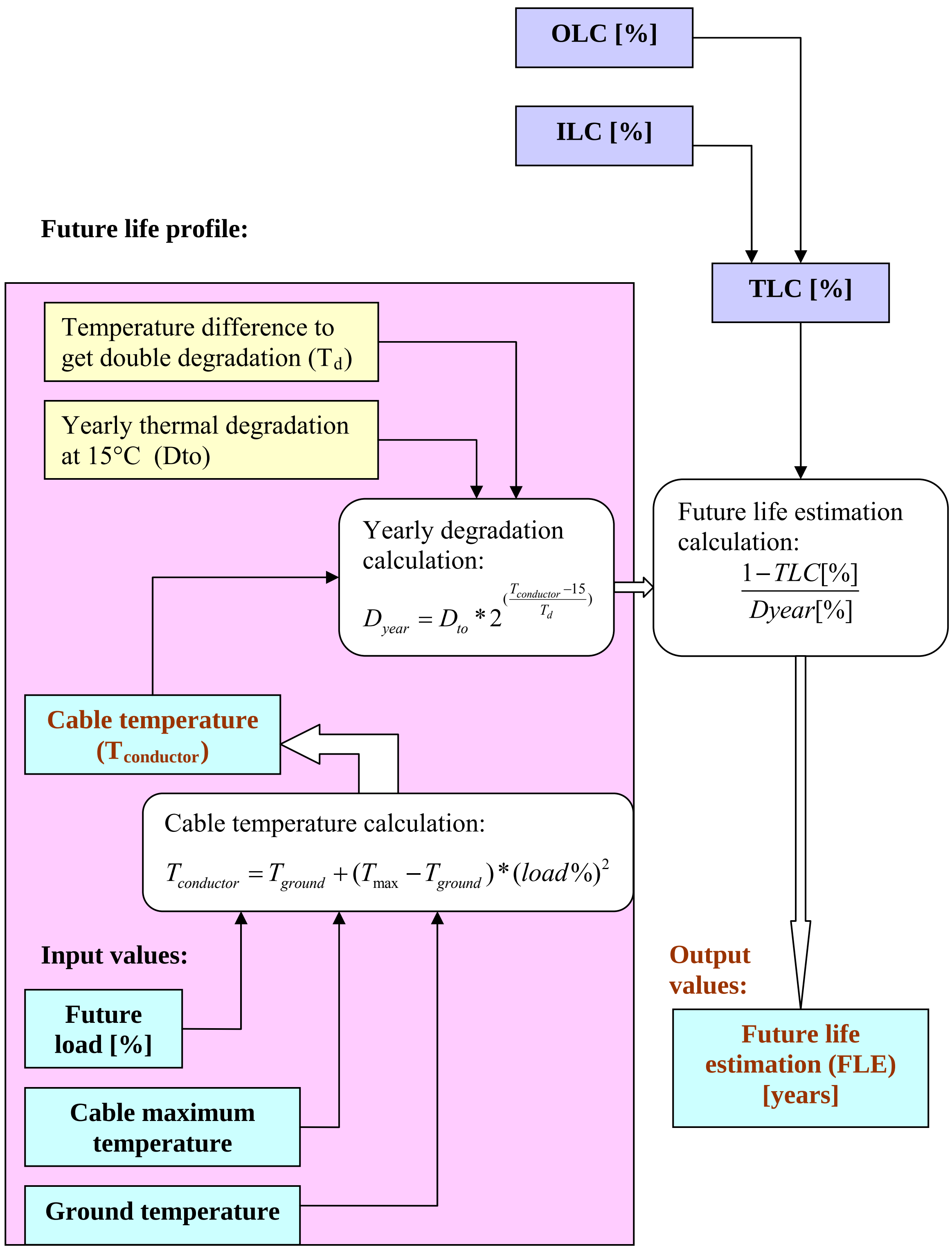


Figure 4.7 Flow chart of FLE calculation

Figure 4.8 shows the interface of future life estimation calculation program in excel. The temperature difference of doubling degradation (Td), degradation rate at 15°C and cable maximum value are the same as OLC calculation. The input values are ground temperature and future load. The output values (in red color) are: cable temperature (Tconductor), yearly degradation rate (Dyear) and future life estimation in years.

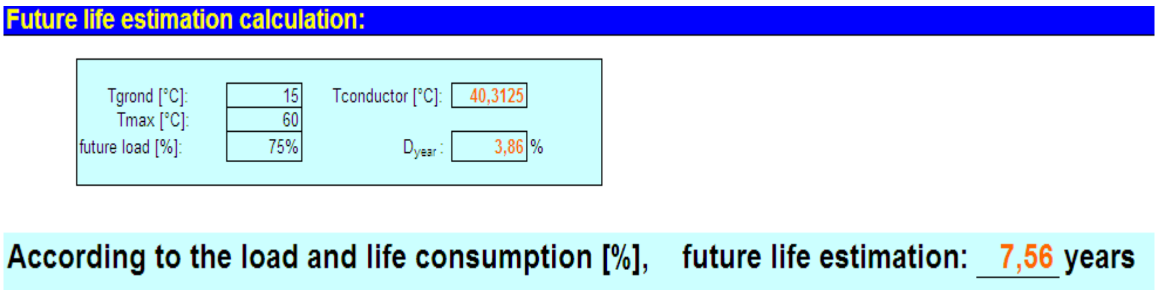


Figure 4.8 the interface of FLE calculation program

5 Model verification

To ensure the applicability for diagnosing life consumption and future life estimation of serviced oil-impregnated paper insulated cables, model verification is needed. The dielectric loss values of two different condition cables are used in the model verification, the first cable is in a bad condition, the second cable is in a very good condition.

5.1 Example of bad condition cable

In table 5.1, a test example of dielectric loss value is shown. The cable type for this example is external gas-pressured mineral oil cable. The cable operated in the Netherlands as an underground cable. The test voltage is from 40kV to 130kV. In the table, the voltage value is recalculated into per unit value. The values of tanδ for three phases are shown in the table. The cable has been in operation for 35 years, the average past load is 35%.

	tan δ [10^{-4}]		
test voltage	phase U	phase V	phase W
0,3Uo	37,71	31,87	30,25
0,4Uo	40,485	34,22	33,97
0,5Uo	42	35,97	33,19
0,6Uo	43,66	35,75	35,6
0,7Uo	44,965	37,09	34,97
0,8Uo	45,38	38,36	37,73
0,9Uo	48,46	41,04	40,43
1Uo	52,72	65,26	59,43

Table 5.1 Dielectric loss value of external gas-pressured mineral oil

1. First step is to calculate the insulation life consumption by tanδ value. The results of life consumption for the three phases are shown in figure 5.1 to figure 5.3. The test voltage values are chosen the lowest voltage 0.3Uo and highest voltage 1Uo. For phase U, the dielectric loss values are $37.71*10^{-4}$ and $52.72*10^{-4}$, for phase V, dielectric loss values are $31.87*10^{-4}$ and $65.26*10^{-4}$, for phase W, dielectric loss values are $30.25*10^{-4}$ and $59.43*10^{-4}$. After the calculation, the ILC for the three phases are 100%, 100% and 100%.

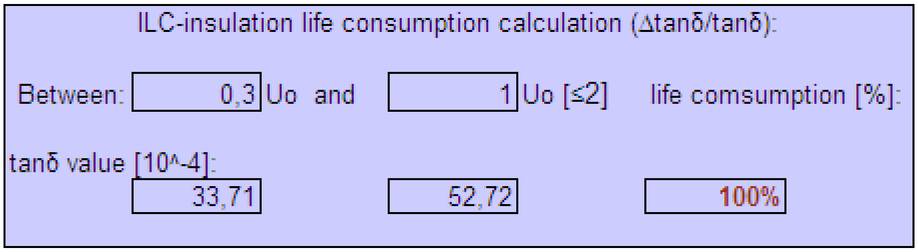


Figure 5.1 ILC calculation of phase U

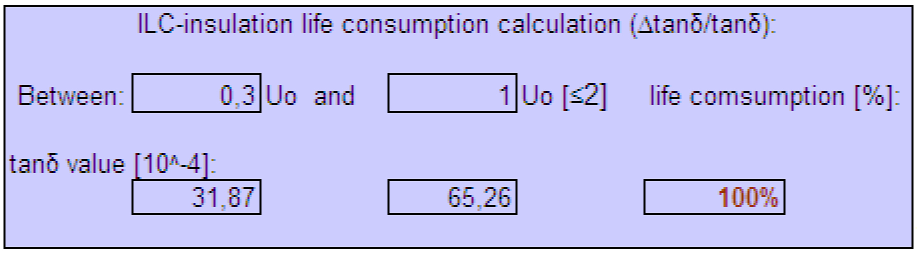


Figure 5.2 ILC calculation of phase V

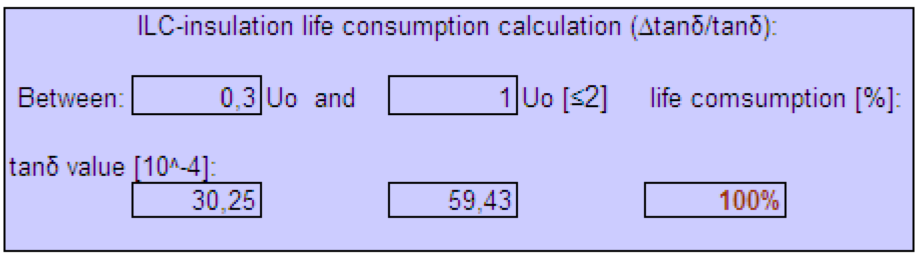


Figure 5.3 ILC calculation of phase W

From the insulation life consumption part, the three phases already come to the end of their life.

2. Second step is to calculate the operational life consumption based on the thermal aging. The cable type is external gas-pressure mineral oil cable, so the temperature difference to get double degradation is 13°C and yearly thermal degradation at 15°C is 1%. According to the operational history, the other input values are: ground temperature 10°C (assume the average ground temperature in the Netherlands is 10°C), cable maximum temperature 60°C, past load applied on the cable 35% and for cable age 35 years. After the calculation, cable temperature is 20.5°C and operational life consumption is 37%.

for the sample:

Td:	13	°C	Temperature difference to get double degradation
Dto:	1	%	Yearly thermal degradation at 15°C

Cable types	Td	Dto	Tmax
External gas-pressure mineral oil cable	13°C	1%	60°C
External gas-pressure synthetic oil cable	21°C	1%	85°C
Paper insulated lead covered (PILC) cable	6,5°C	0,5%	43°C

OLC-operational life consumption calculation (past load)

Tgrond [°C]:	10	Tconductor [°C]:	
Tmax [°C]:	60		16,125
past load [%]:	35%	life consumption [%]:	
cable age [years]:	35		37%

Figure 5.4 OLC calculation based on thermal aging

3. The third step is to combine the two results by using the method discussed in chapter 4. The results for the three phases are all 100%. Thus ILC takes 50% weight and OLC takes 50% weight. The OLC value based on thermal aging is 37%. Thus the total life consumption value is 100%*0.5+37%*0.5=69%. The result is shown in figure 5.5.

Taking into account both life consumption results, TLC-total life consumption [%]: 69%

Figure 5.5 TLC value

4. The forth step is to calculate the future life estimation. The ground temperature and cable maximum temperature are 10°C and 60°C respectively. The calculation can be separated to three situations:

a) The future load keeps the same as past load 35%. After the calculation, the cable temperature will be 16.1°C, yearly degradation is 1.06% and the maximum future life expectancy is 29.6 years. The result is shown in figure 5.6.

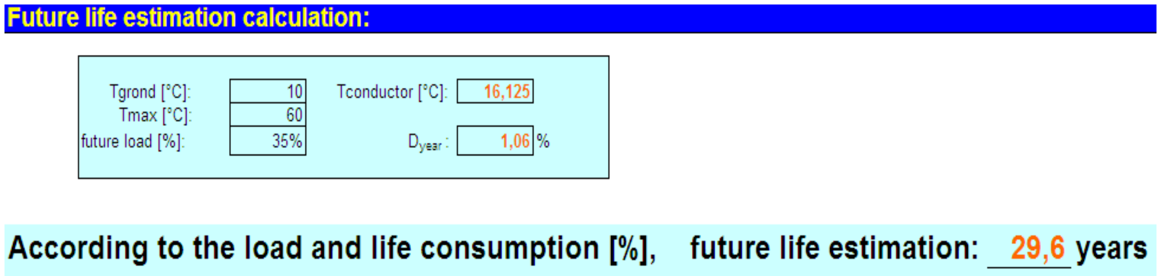


Figure 5.6 FLE calculation when future load is 35%

b) The future load increases to the maximum 100% load. After calculation, the cable temperature is 60°C, yearly degradation is 11.02%, the maximum future life estimation is 2.85years. The result is shown in figure 5.7.

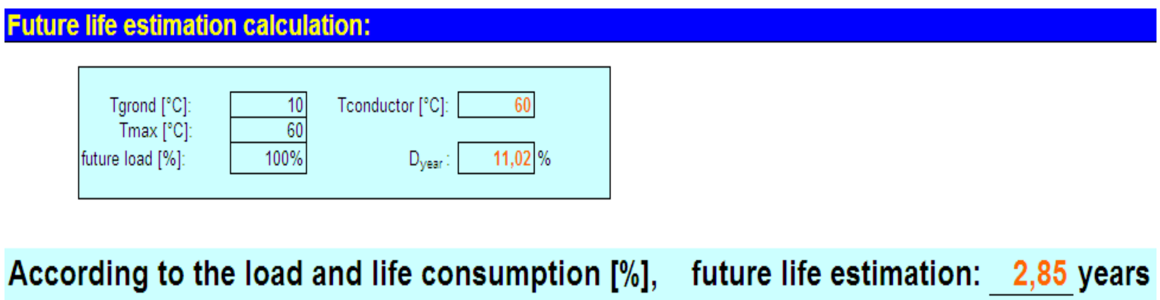


Figure 5.7 FLE calculation when future load is 75%

c) The future load decreases to a optimal load which is 20%. After calculation, the cable temperature is 12°C, yearly degradation is 0.85%, the maximum future life estimation is 36.9years. The result is shown in figure 5.8.

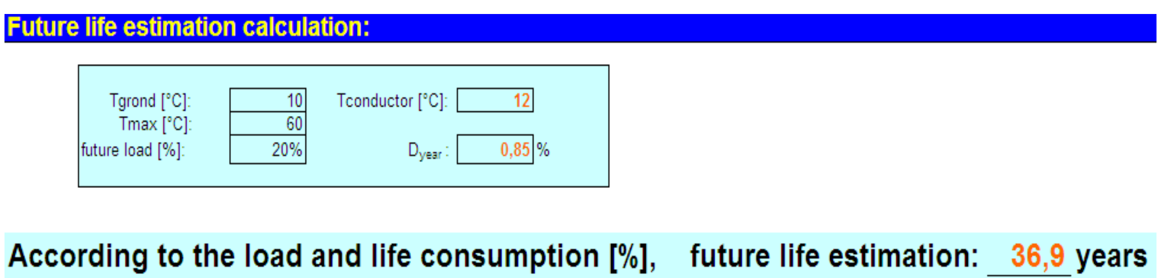


Figure 5.8 FLE calculation when future load is 20%

From the life consumption and future life estimation calculation of the cable, it can be seen that for the insulation life consumption part, this cable is in a bad condition, the cable comes to the end of the life. But for the operational life consumption part, the cable is 37% degradation when the load is 35%. Taking into account both ILC and OPC, the total life consumption is 69%. Based on TLC value, the future life estimation is calculated. When the load keeps as 35%, the maximum future life estimation of cable is 29.6 years. When the load increases 100%, the maximum future life estimation of cable is only 2.85 years. When the load decreases 20%, the maximum future life estimation of cable is 36.9 years.

5.2 Example of good condition cable

In table 5.2, a test example of dielectric loss value is shown. The cable type for this example is external gas-pressured mineral oil cable. The cable was used in the Netherlands as underground high voltage cable. The test voltage is from 40kV to 150kV. In the table, the voltage value is recalculated into per unit value. The values of tanδ for three phases are shown in the table. The cable has been in operation for 35 years, the average past load is 40%.

	tan δ [10^{-4}]		
test voltage	phase U	phase V	phase W
0,3Uo	18,15	17,15	17,69
0,4Uo	19,07	17,63	17,47
0,5Uo	16,87	16,4	14,81
0,6Uo	18,14	16,61	15,34
0,7Uo	17,61	17,29	16,16
0,8Uo	17,67	17,04	16,69
0,9Uo	18,07	17,29	16,83
1Uo	19,29	18,13	17,23
1.1Uo	20,01	18,87	18,56
1.2Uo	20,74	20,27	18,89

Table 5.2 Dielectric loss value of external gas-pressured mineral oil

1. First step is to calculate the insulation life consumption by tanδ value. The results of life consumption for the three phases are shown in figure 5.9 to figure 5.11. For the highest and the lowest test voltage values 0.3Uo and 1.2Uo are chosen. For phase U, the dielectric loss values are $18.15*10^{-4}$ and $20.27*10^{-4}$, for phase V, dielectric loss values are $17.15*10^{-4}$ and $20.27*10^{-4}$, for phase W, dielectric loss values are $17.69*10^{-4}$ and $18.89*10^{-4}$. After the calculation, the ILC for the three phases are 20%, 25% and 9%.

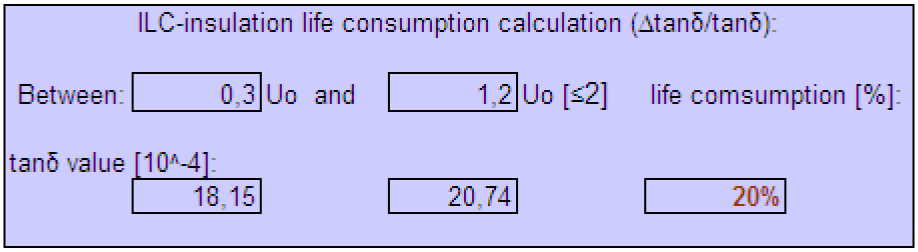


Figure 5.9 ILC calculation for phase U

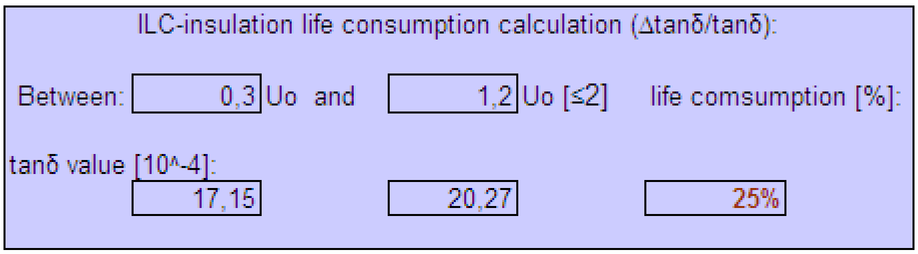


Figure 5.10 ILC calculation for phase V

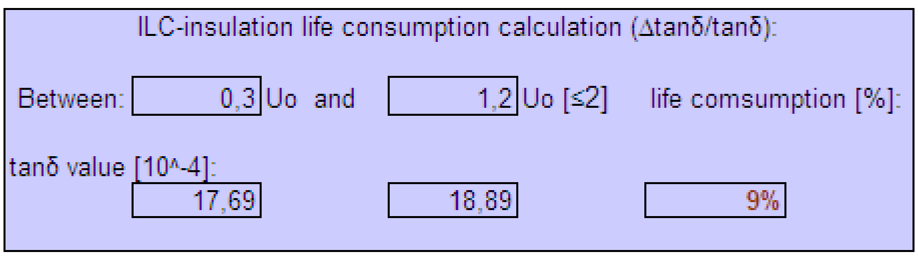


Figure 5.11 ILC calculation for phase W

2. Second step is to calculate the operational life consumption based on the thermal aging. The cable type is external gas-pressure mineral oil cable, so the temperature difference to get double degradation is 13°C and yearly thermal degradation at 15°C is 1%. According to the operational history of the cable, the other input values are: ground temperature is 10°C, cable maximum temperature is 60°C, past load on the cable is 40% and cable age is 35 years. After the calculation, cable temperature is 18°C and operational life consumption is 41%. The result is shown in figure 5.12.

for the sample:

Td:	13	°C	Temperature difference to get double degradation
Dto:	1	%	Yearly thermal degradation at 15°C

Cable types	Td	Dto	Tmax
External gas-pressure mineral oil cable	13°C	1%	60°C
External gas-pressure synthetic oil cable	21°C	1%	85°C
Paper insulated lead covered (PILC) cable	6,5°C	0,5%	43°C

OLC-operational life consumption calculation (past load)

Tgrond [°C]:	10	Tconductor [°C]:	
Tmax [°C]:	60		18
past load [%]:	40%	life consumption [%]:	
cable age [years]:	35		41%

Figure 5.12 OLC calculation based on thermal aging

3. The third step is to combine the two results by using the method discussed in chapter 4. The results for the three phases are 25%, 20% and 9%. The ILC differences between the three phases are larger than 5%. Thus ILC takes 70% weight and OLC takes 30% weight. The OLC value based on thermal aging is 41%. And the ILC value is the average value of the three phases, it is 18% Thus the total life consumption value is 18%*0.7+41%*0.3=25%. The result is shown in figure 5.13.

Taking into account both life consumption results, TLC-total life consumption [%]:	**25%**

Figure 5.13 TLC value

4. The forth step is to calculate the future life estimation. The ground temperature is 10°C and the cable maximum temperature is 60°C. The calculation can be separated to two situations:

a) The future load keeps the same as past load which is 40%. After the calculation, the cable temperature will be 18°C, yearly degradation is 1.17% and future life estimation is 63.9 years. The result is shown in figure 5.14.

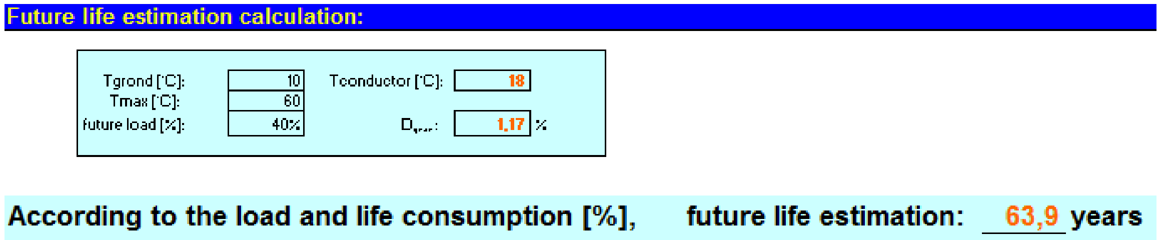


Figure 5.14 FLE calculation when future load is 40%

b) The future load increases to the maximum 100% load. After the calculation, the cable temperature will be 60°C, yearly degradation is 11.02% and future life estimation is 6.81 years. The result is shown in figure 5.15.

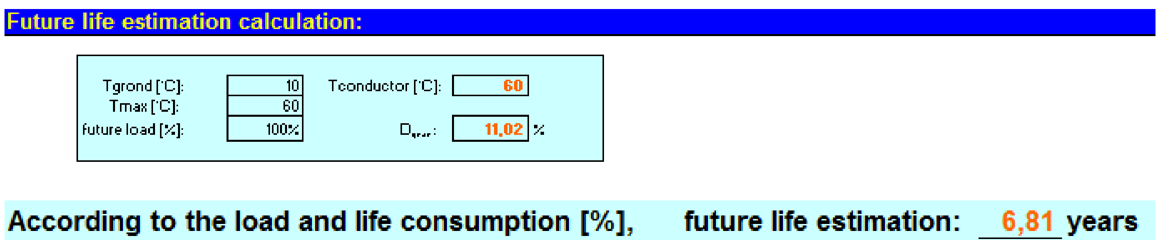


Figure 5.15 FLE calculation when future load is 100%

From the life consumption and future life estimation calculation of the cable, it can be seen that for the insulation life consumption part, this cable is in a good condition, the ILC of three phases are 20%, 25% and 9%. But for the operational life consumption part, the cable is 41% degradation when the load is 40%. Taking into account both ILC and OPC, the total life consumption is 25%. Based on TLC value, the future life estimation is calculated. When the load keeps 40%, the cable still can be used for at most 63.9 years. When the load is 100%, the cable still can be used for at most 6.8 years.

5.3 Future load modeling of the two cable examples

When the ground temperature is 10°C, the yearly degradation rate and total life time of oil-impregnated paper insulated cable depend on the load of the cable. The relations between future degradation rate, future life estimation and percentage of load are shown in table 5.3.

bad condition cable				good condition cable			
TLC	Future load [%]	Future degradation rate [%]	Future life estimation [years]	TLC	Future load [%]	Future degradation rate [%]	Future life estimation [years]
69% (past load 35%)	20	0,85	36,9	25% (past load 40%)	20	0,85	88
	25	0,9	34,7		25	0,9	82,9
	30	0,97	32,3		30	0,97	77
	35	1,06	29,6		35	1,06	70.6
	40	1,17	26,8		40	1,17	63.6
	50	1,49	21,1		50	1,49	50.3
	75	3,43	9,16		75	3,43	21.9
	100	11,02	2,85		100	11,02	6.81

Table 5.3 relation between cable yearly degradation rate and load

Table 5.3 shows:

- The degradation rate increases with the load. When the future load is 20%, the degradation rate of cable is 0.85%; when the future load is 100%, the degradation rate is 11.02%.
- Future life estimation decreases with the load. When the future load is 20%, future life estimations of bad condition cable and good condition cable are 36.9 years and 88 years respectively; when the future is 100%, future life estimations of bad condition cable and good condition cable are 2.85 years and 6.81 years respectively
- Future life estimation also depends on the total life consumption of the cable. When the future loads are the same, future life estimation of good condition cable is more than twice as long as that of bad condition cable.

In figure 5.16 and figure 5.17, the future load modeling of bad condition cable and good condition cable are shown, the first part is a single brown line which shows the past degradation of the cable, the second part contains different color lines which shows the future life estimations when the future load is different.

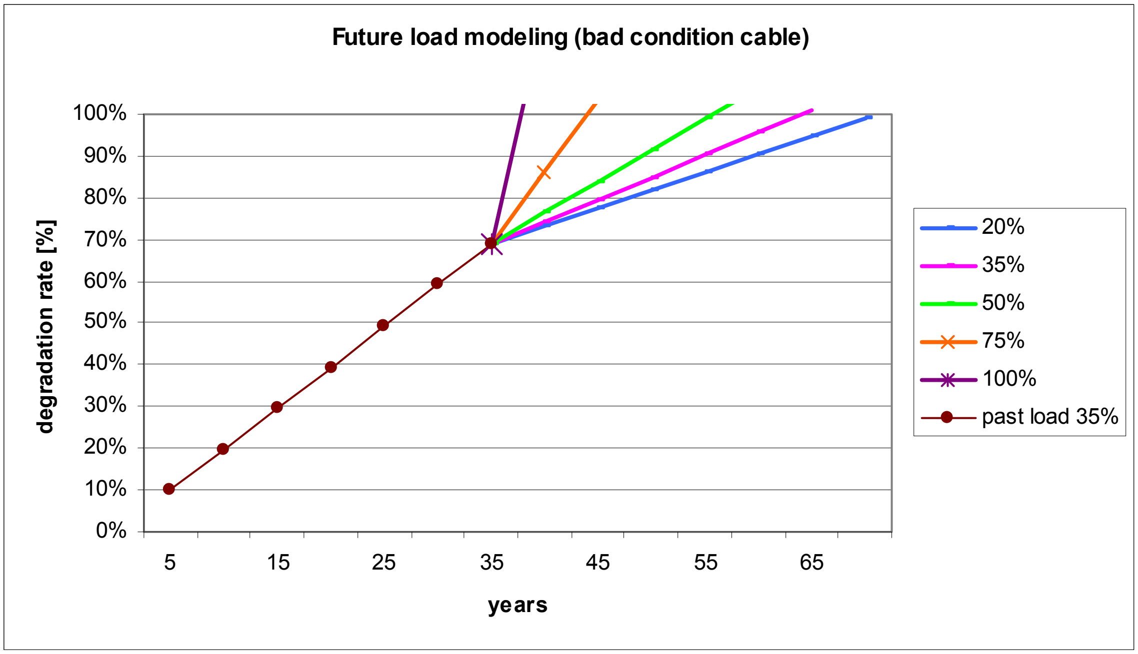


Figure 5.16 Future load modeling of bad condition cable

From chapter 5.1, it's already known that the bad condition cable has 69% life consumption, the past load is 35% and the cable has been operated for 35 years. Thus in figure 5.16, the degradation rate of the bad condition cable from 0 to 35 years is shown as a brown line; it combines both the operational degradation due to the past load and insulation life degradation based on dielectric loss value. For the future life estimation, only the thermal aging is considered. After 35 years, if the load on the cable is 20%, the future life estimation is 36.9 years; if the load is kept at 35%, the future life estimation is 29.6 years; if the load is increased to 50%, the future life estimation is 21.1 years; if the load is increased to a very high value, 75% and 100%, the future life estimation are 9.16 years and 2.85 years respectively.

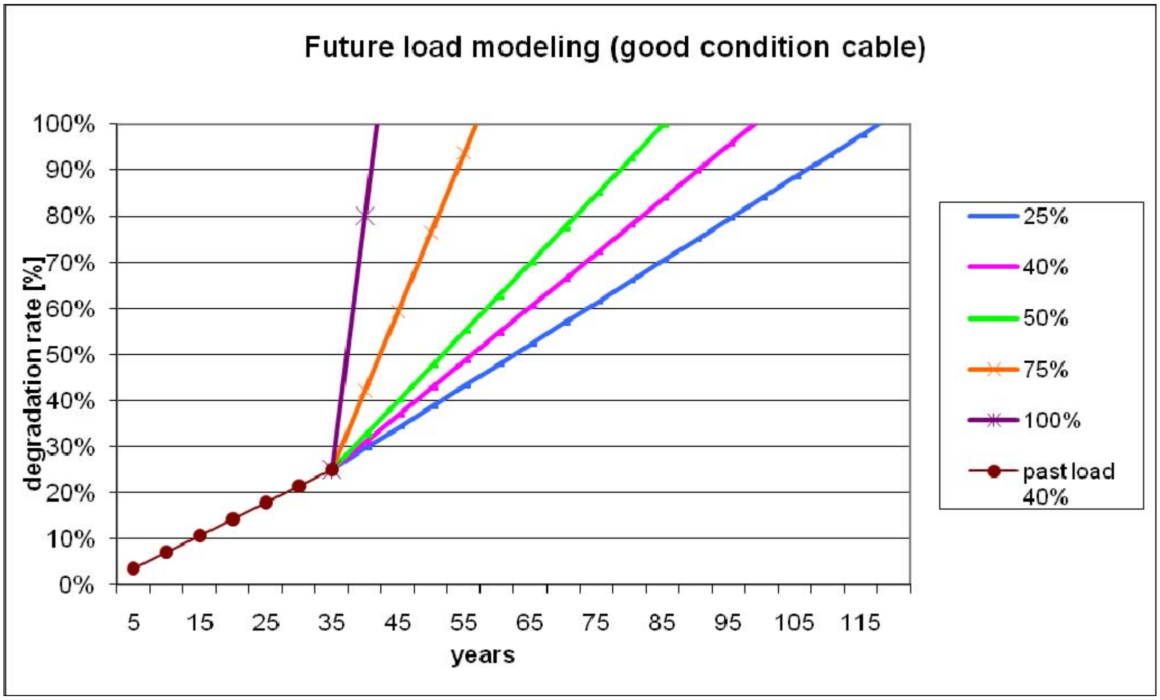


Figure 5.17 Future load modeling of good condition cable

In figure 5.17, the life consumption and future life estimation of good condition cable are shown. From chapter 5.2, it's already known that the life consumption of the good condition cable is 25%, the past load is 40%, and the cable has been operated for 35 years. The degradation rate of the good condition cable combines the operational degradation due to the thermal aging and insulation degradation based on dielectric loss value. The degradation rate of the good condition cable from 0 to 35 years is shown as a brown line. The future life estimation only considers the thermal aging due to the future load. Thus, if the load on the cable is 25%, future life estimation is 82.9 years; if the load is kept 40%, the future life estimation is 63,6 year; if the load is increased to 50%, the life estimation decreases to 50,3 years; if the load is increased to 75% and 100%, the life estimations are 21.9 years and 6.81 years respectively.

5.4 Conclusions of the model verification

1. The ILC calculation depends on the tanδ value of the cable insulation. The ILC values of the three phases of bad condition cable are all 100%, the ILC values of the three phases of good condition cable are 20%, 25% and 9%.
2. The OLC calculation depends on the operational history: ground temperature, past load, cable age and cable type. The OLC value of bad condition cable is 37%, the OLC value of good condition cable is 41%.
3. From the two examples of difference condition cables, it can be seen that the ILC and OLC calculations are independent from each other. The bad condition cable has a 37% OLC value and 100% ILC value, the good condition cable has a 41% OLC value and an 18% average ILC value for the three phases.
4. The total life consumption combines ILC and OLC values, so the bad condition cable has 69% life consumption and the good condition cable has 25% life consumption.
5. The future life estimation depends on the TLC and future load. Because the other operational conditions, ground temperature and cable type are the same as the past. When future load is 25%, the bad condition cable can be operated for 34.7 years and the good condition cable can be operated for another 82.4 years. When future load is 75%, bad condition cable can be operated for 9.16 years and good condition cable can still be operated for 21.9 years.
6. The ILC calculation in the model helps qualify the level of insulation degradation of a particular oil-impregnated paper cable circuit.
7. Based on OLC calculation in the model, the effect of operational history and thermal aging can be estimated.
8. Using the FLE calculation, future decisions about the permissible load profile and expected life-time can be supported.

6 Conclusions

In this thesis, dielectric loss measurement is presented as an additional tool for diagnosing the life consumption of oil-impregnated paper insulated cable. Dielectric loss values were investigated at different temperatures and different electrical field intensities in the laboratory. Based on laboratory measurements, a program was built which can calculate the life consumption of paper oil-impregnated insulation by on-site dielectric loss measurements. Thermal aging was also taken into account for life consumption calculation in the program as an additional criterion. After that, future life estimation is calculated based on the result of life consumption and thermal aging theory in the program.

From the research provided by this thesis it can be learned that:

1. Oil impregnated paper has been used since the earliest days of cable development and even today constitutes one of the most extensively used cable insulations. For the oil-impregnated paper insulated cable, the life time is mainly influenced by thermal aging. Thermal aging can be described by the formula of Arrhenius Law. Dielectric loss value is a useful tool to assess the condition of oil-impregnated paper insulation, and is therefore used in this thesis for diagnosing the life consumption of oil-impregnated paper insulation.

2. Due to the characteristics of the structure of porous paper and mineral oil, there are four stress factors that influence the insulation, electrical stress, thermal stress, mechanical stress and environment stress. In the lab, only the electrical stress and thermal stress are investigated. Dielectric loss value increases with electrical field intensity due to the polarization of ions, however, when the thermal and electrical stresses are very high, dielectric loss value decreases with electrical field intensity due to Garton effect. When the electrical field intensity is constant, dielectric loss value increases with temperature due to viscosity decreasing. In this part, electrical aging and thermal aging are also introduced.

3. In the laboratory, oil-impregnated paper is subjected to accelerated thermal aging in the temperature of 110°C. During the test, different electrical field intensities and temperatures are applied to the samples. The measurements lasted for 225 days to test the samples from 1% to 100% life consumption. The goals of these tests were to analyze the relation between life consumption and dielectric loss value at certain temperatures and certain electrical field intensities. The investigations of the influence of electrical field intensity and temperature showed that: dielectric loss increases with electrical field intensity at low temperature, dielectric loss decreases with electrical field intensity at high temperature, and dielectric loss increases with temperature. By life consumption analysis, it can be seen that at low temperatures, dielectric loss value increases exponentially with life consumption at certain applied voltage, dielectric loss value increases linearly with voltage, and $\Delta\tan\delta$ increases exponentially with life consumption. Based on these results, it was proven that the relative $\tan\delta$ value changes linearly with life consumption and voltage, so relative $\tan\delta$ values are used in the calculation of life consumption.

4. A program was built for life consumption calculation and future life estimation. For life consumption calculation, relative $\tan\delta$ value and thermal aging are both taken into account. ILC (insulation life consumption) calculation based on the relative $\tan\delta$ value uses the formula fitted by data analysis. OLC (operational life consumption) calculation is based on thermal aging. The calculation of TLC (total life consumption) is the combination of the ILC and OLC results. The FLE (future life estimation) is based on the final result of TLC and calculated by using the formula of Montsinger law.

5. The program was verified and using the results of dielectric loss measurements for two cables of different condition. It can be seen that ILC and OLC calculations are independent from each other. The TLC combines both ILC and OLC. Thus the FLE calculation takes both insulation degradation and operational degradation into account. The model can be used to qualify the degradation of oil-impregnated paper insulated cable, and to estimate the effect of operational history on the cable. Finally it can support the decision about future load profile and expected life.

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Appendix

Abbreviation

$T_{conductor}$ – the cable temperature

T_{ground} – the ground temperature

T_{max} – the maximum temperature of the cable

Load% – the percentage of the load.

D_{year} – yearly degradation

D_{to} – yearly thermal degradation at 15°C

T_d – temperature increase causing the insulation degradation double

Uo – nominal voltage

tanδ – dielectric loss value

Δtanδ – increase of dielectric loss

PD – partial discharge

ILC – insulation life consumption [%]

OLC – operational life consumption [%]

TLC – total life consumption [%]

FLE – future life estimation [Years]

Formulas:

1. $$\frac{T_{conductor} - T_{ground}}{T_{\max} - T_{ground}} = \frac{I^2}{I_{\max}{}^2}$$

2. $$\frac{I^2}{I_{\max}{}^2} = (load\%)^2$$

3. $$T_{conductor} = T_{ground} + (T_{\max} - T_{ground}) * (load\%)^2$$

4. $$k = A \cdot e^{(-Ea/R \cdot T)}$$

5. $$D_{year} = D_{to} * 2^{\left(\frac{T_{conductor} - 15}{T_d}\right)}$$

6. $W = U \cdot I_C \tan\delta = U^2 \omega C \tan\delta$

7. $\tan\delta = \frac{I_r}{I_c} = \frac{1}{\omega \cdot R \cdot C}$

8. $lab\_\tan\delta = f(U,T)$

9. $life\_consumption[\%] = f(\tan\delta, U)$

10. $field\_\tan\delta = f(U)$

11. $Z_3 Z_s = Z Z_4$

12. $\tan\delta = \omega R_4 C_4$

13. $E = \frac{U}{x \cdot \ln\frac{R}{r}}$

14. $relative\_\tan\delta = \frac{\tan\delta(U2) - \tan\delta(U1)}{\tan\delta(U1)}$

15. $ILC[\%] = 10 * \frac{0.09}{U_2 - U_1} * 1.1^{\frac{U_1}{0.09}} * \frac{\tan\delta(U_2) - \tan\delta(U_1)}{\tan\delta(U_1)}$

Application of dielectric loss measurements for life consumption and future life estimation modeling of oil-impregnated paper insulation in HV power cables

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Abstract— **This paper gives the information about application of dielectric loss measurements for life consumption and future life estimation of oil-impregnated paper insulated cable. This is done by combination of laboratory experiment and on-site diagnostics. During laboratory experiment dielectric loss values were investigated at different temperatures and different electrical field intensities for samples characterized by different life consumption. Based on laboratory measurements, a program was built; it can calculate the life consumption of paper oil-impregnated insulation by using the results of on-site dielectric loss measurements. Future life estimation is calculated based on the result of life consumption and thermal aging theory in the program. Thus the program can be used to qualify the degradation of oil-impregnated paper insulated cable, estimate the effect of operational history of the cable and support the future decisions of load profile and expected life of the cable.**

Keywords- dielectric los; tanδ; serviced power cables; aging; oil-impregnated insulation; life consumption; future life estimation

I. INTRODUCTION

Dielectric loss measurement is a useful tool to assess the condition of oil-impregnated paper insulation [5, 6]. The condition of the oil-impregnated paper insulated cables can be determined by on-site diagnosis. In particular, dielectric loss (tanδ) can be measured in function of test voltage as the tanδ value indicates the condition of the cable insulation. To be able to determine the life consumption and future life estimation, a model is needed to relate dielectric loss in function of test voltage with life expectancy. By using the model, insulation life consumption can be calculated by tanδ values. On the other hand, thermal aging plays an important role in the aging process of a cable system. Thus in the model, the operational life consumption OLC due to the past load based on thermal ageing theory is also taken into account. It's known that for serviced aged cable system, increase of load will accelerate the aging process even more. So future life estimation of the cable is calculated by using information about future load. The model is based on the laboratory investigation into oil-impregnated paper insulation.

II. LABORATORY INVESTIGATION

In the laboratory, the tanδ values are measured by Schering Bridge. In the left part Figure 1, the setup of dielectric loss measurements is shown. The test object is oil-impregnated paper insulation. The test object is placed between the two electrodes. The normal configuration setup has two circular electrodes and a ring electrode around the low voltage electrode. Guard electrode eliminates surface leakage current which can affect the loss factor measurement. The set of these electrodes are placed in one of the arms of Schering bridge. In the right part of Figure 1, the electrodes are depicted.

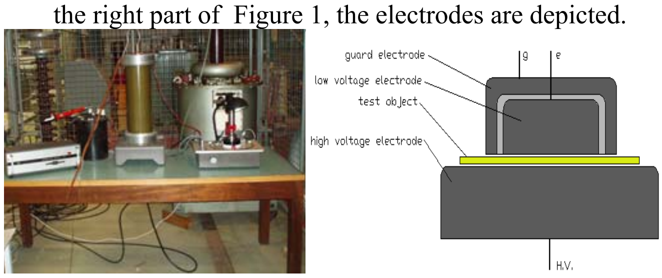

Figure 1. Test setup of dielecrtric loss measurements and cross section of the electrodes

The samples of oil-impregnated paper insulation are investigated; these samples are subjected to the accelerated aging in thermally controlled oven. The tests last for 225 days, and 40 samples are tested. Thus the 40 samples represent the 40 different percentage of life consumption of oil-impregnated paper insulation between 1% and 97% life consumption. The samples are subjected to different electrical stress from 0.7kV/mm to 6.1kV/mm and different thermal stresses from 25°C to 80°C.

A) Inflence of electrical field intensity on tanδ value

During on-site diagnosis, dielectric loss value is measured at low temperature, so the influence of electrical field intensity on paper insulation at low temperature is important for the analysis of relation between dielectric loss value, voltage and life consumption.

The influence of electrical field intensity on paper insulation at low temperature can be deducted from the fact that he conduction in impregnated paper can be described according to the motion of ions in oil. The ionic motion increases with electrical field intensity [1] Thus the tanδ value exhibits a linear increase with applied voltage, which is shown in figure 2. Moreover, aged paper insulation contains more pores and impurities due to degradation, which increases tanδ dependence on electrical field.. In figure 2, different lines indicate different life consumption. It can be seen that the increase of tanδ becomes larger when the life consumption is higher.

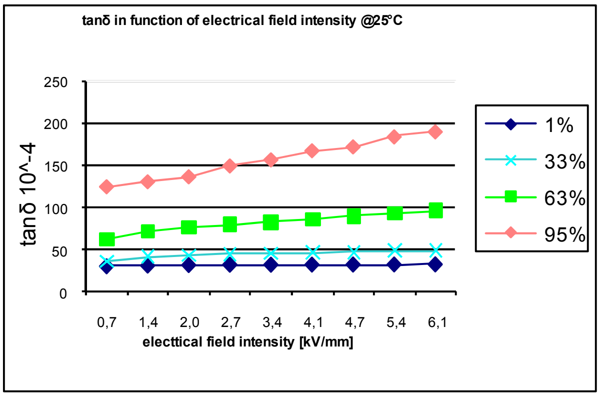

Figure 2. tanδ value in function of electrical field intensity at 25°C

B) *Inflence of temperature on tanδ value*

The influence of temperature on the insulation is due to the fact that oil viscosity decreases with temperature [1]. When oil viscosity becomes lower, the ionic motion in the oil becomes higher; this causes the increase of dielectric loss which is shown in figure 3.When the paper insulation gets a higher degradation, there are more impurities which increase the oil conductivities even higher with the temperature. Thus the increase of dielectric loss becomes higher. In figure 3 different color indicates different life consumption, when the life consumption of the paper insulation is higher, the increase is larger

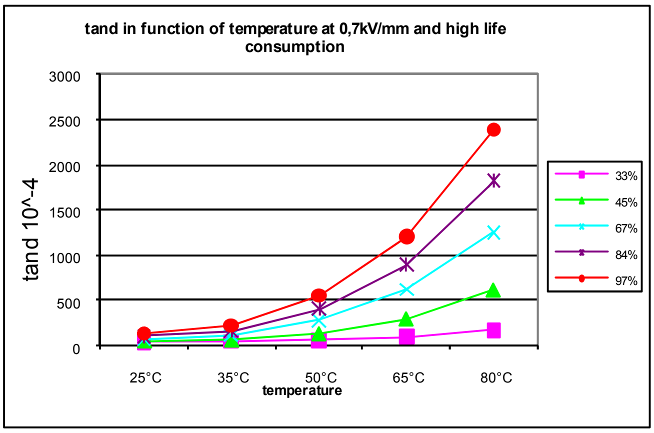

Figure 3. tanδ value in function of temperature at high life consumption .

III. DATA ANALYSIS

The data obtained in the experiment are analyzed to establish the relation between life consumption and the tanδ value at different applied voltage. This relation is needed to build a model for diagnosing life consumption and future life estimation of oil-impregnated paper insulated cable. In this analysis the electrical field intensity applied to the insulation samples during laboratory testing is transferred to per unit voltage value applied to the cable.

Relative tanδ value is chosen for the modeling. The reason for choosing relative tanδ value instead of Δtanδ is that the tanδ value obtained by laboratory measurements is different from the one obtained tanδ on-site diagnosis, but for relative tanδ value, the laboratory values and those obtained during on-site measurements are similar. The relative tanδ value is given by:

$$relative\_\tan\delta = \frac{\tan\delta(U2) - \tan\delta(U1)}{\tan\delta(U1)} \qquad (1)$$

In figure 4, relative tanδ (U1=0.19Uo) value in function of applied voltage difference is shown. Different color lines indicate different life consumption of the insulation. it can be seen that the relative tanδ value increases linearly voltage difference. For more degraded paper insulation, the increase is bigger.

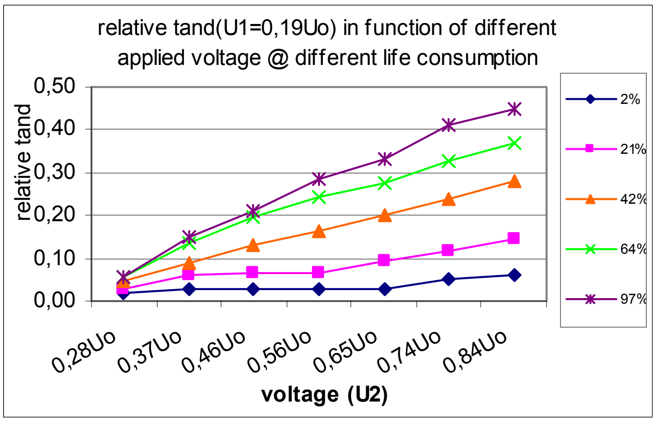

Figure 4. relative tanδ(U1=0.19Uo) in function of voltage difference at different life consumption

Thus by using these results, a formula can be fitted to calculate life consumption by relative tanδ value:

$$ILC[\%] = 10 * \frac{0.09}{U_2 - U_1} * 1.1^{\frac{U_1}{0.09}} * \frac{\tan\delta(U_2) - \tan\delta(U_1)}{\tan\delta(U_1)} \qquad (2)$$

It can be seen that relative tanδ value has a linear relation with life consumption, and the steepness of the linear equation depends on the voltage difference and lower voltage U1. So by using this formula, inputting two different voltage values U1 and U2 (U2>U1) and two tanδ values, the life consumption (Insulation Life Consumption ILC) can be calculated.

IV. LIFE CONSUMPTION AND FUTURE LIFE ESTIMATION MODELING

As introduced in previous paragraph, the relative tanδ value changes linearly with voltage and life consumption. Thus, it can be stated that the relative tanδ value which is measured at low temperature during on-site diagnosis, may be used as a tool to assess the life consumption of oil-impregnated paper insulation. A second method to diagnose the life consumption of the insulation is based on thermal aging and Arrhenius Law (Operational Life Consumption OLC). The future life estimation is based on both thermal aging and the result of life consumption calculated by relative tanδ value. The two calculations of life consumption should take different weights to be combined together.

A) Insulation life consumption (ILC) calculation

In figure 5, the flowchart of program of ILC calculation by relative tanδ value is shown. Input values are Test voltages U1 ,U2 and tanδ(U1) ,tanδ(U2) The output is the percentage of insulation life consumption.

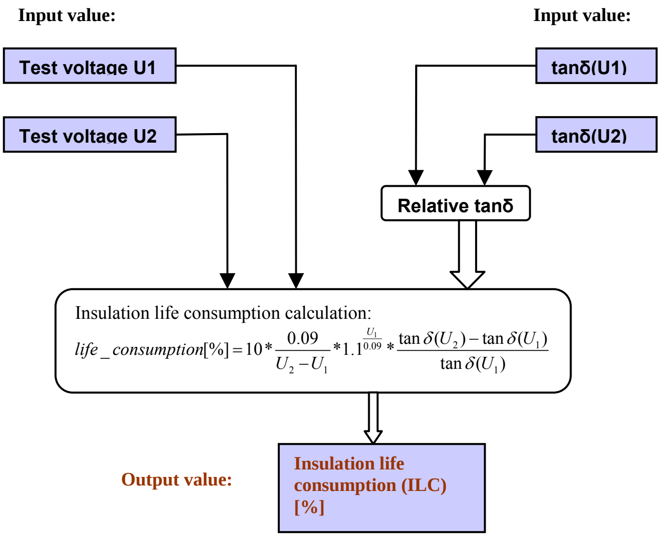

Figure 5. Flow chart of ILC calculated by relative tanδ value

In figure 6, the interface of ILC calculation program in excel is shown. The upper row shows the two input voltage values, U1 and U2 in per unit value. The lower row shows the two input tanδ values, tanδ(U1) and tanδ(U2) and the output insulation life consumption value.

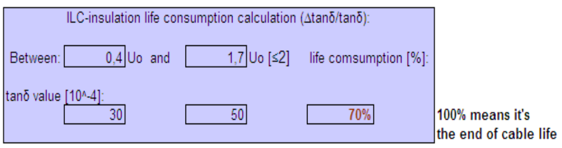

Figure 6. the interface of ILC calculation program

B) Operational life consumption (OLC) calculation

The operational life consumption calculated by past load is based on the Arrhenius law [3]. Arrhenius law describes the relation between temperature and degradation rate, which shows that the temperature has an exponential influence on the degradation rate of the insulation. The Arrhenius Law is shown below:

$$k = A \cdot e^{(-Ea/R \cdot T)} \quad (3)$$

Where: k is the reaction rate coefficient, A is constant (maximum speed reaction), Ea is the activation energy (energy that has to be delivered to start the reaction), R.T is the average energy the molecule has at certain temperature, R is the molecule gas constant (8,314472 [J $K^{-1}mol^{-1}$], T is the absolute temperature.

Figure 7 shows the flow chart of operational life consumption calculated by past load. Cable temperature is calculated by the load. Then the result of cable temperature and other cable parameters are inputted into the calculation of yearly degradation of the cable. After that, the result of yearly degradation of cable and cable age are inputted into the OLC calculation.

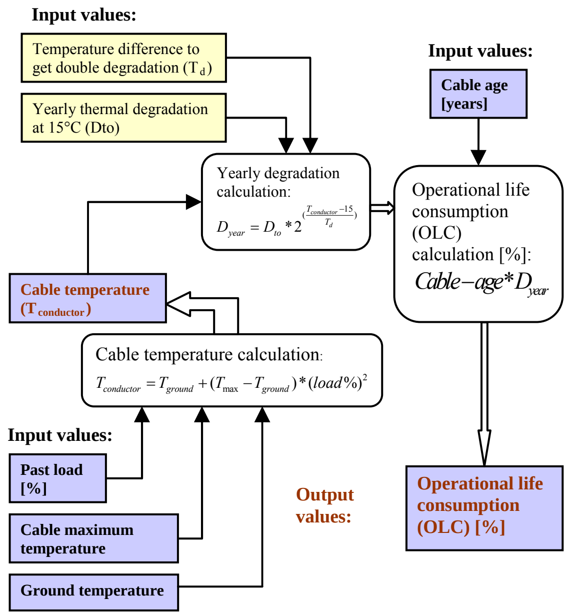

Figure 7. Flow chart of OLC calculation by past load

In Figure 8, the interface of operational life consumption calculation in excel is shown. The parameters of three different type cable are shown in figure. Below that, it is shown that when T_{ground}, T_{max}, percentage of past load and cable age are input values, the results are cable temperature ($T_{condutor}$) and operational life consumption.

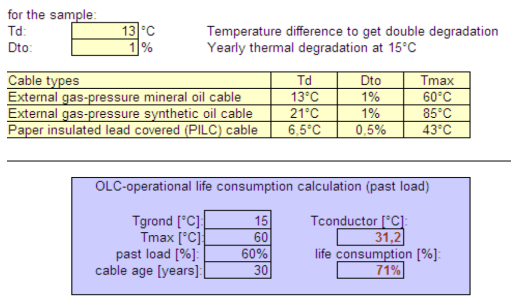

Figure 8. the interface of OLC calculation by past load

C) Total life consumption (TLC) calculation

The future life estimation calculation is based on the result of ILC and OLC. By combination of the two results total life consumption (TLC) is obtained. The ILC results of the three phases are compared, if the difference is smaller than 3%, ILC takes 50% weight, and OLC takes 50% weight; If the difference is larger than 3% and smaller than 5%, ILC takes

60% weight, and OLC takes 40% weight; If the difference is larger than 5%, ILC takes 70% weight, and OLC takes 30% weight. So the total life consumption value depends on the difference of ILC value between each phase.

D) Future life estimation(FLE) calculation

The calculation of future life estimation is based on total life consumption and thermal aging. Figure 9 shows the flow chart of calculation of future life estimation. Until the calculation of yearly degradation, the procedure is similar to the life consumption calculation by past load, only now the future applied load should be taken instead of past load value. After that, the result of total life consumption is inputted. The output value, future life estimation, is based on the percentage of total life consumption and yearly degradation.

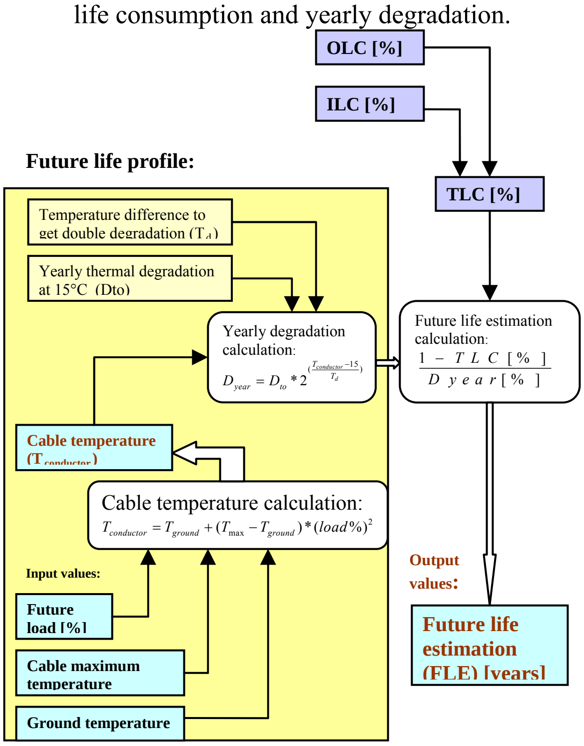

Figure 9. Flow chart of FLE calculation

Figure 10 shows the interface of future life estimation calculation program in excel. The input values are ground temperature and future load. The output values are: cable temperature ($T_{conductor}$), yearly degradation rate (D_{year}) and future life estimation in years.

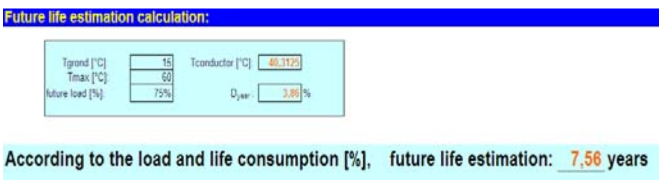

Figure 10. the interface of FLE calculation program

V. CONCLUSIONS

Based on the laboratory investigation, a model is built to calculate insulation life consumption (ILC) by relative tanδ value. The operational life consumption (OLC) calculated by thermal aging is also taken into account in the model. The total life consumption is based on the ILC and OLC results. The future life estimation (FLE) is based on the TLC and thermal aging. The model can be concluded as:

- The ILC calculation depends on the tanδ value of the cable insulation.
- The OLC calculation depends on the operational history: ground temperature, past load, cable age and cable type.
- ILC and OLC can be calculated independent from each other.
- The total life consumption combines ILC and OLC values.
- The future life estimation depends on the TLC and future load.
- The ILC calculation in the model helps to qualify the level of insulation degradation of a particular oil-impregnated paper cable circuit.
- Based on OLC calculation in the model, the effect of operational history and thermal aging can be estimated.
- Using the FLE calculation, future decisions about the permissible load profile and expected life-time can be supported.

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Application of dielectric loss measurements for life consumption and future life estimation modeling of oil-impregnated paper insulation in HV power cables

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Abstract— **This paper gives the information about application of dielectric loss measurements for life consumption and future life estimation of oil-impregnated paper insulated cable. This is done by combination of laboratory experiment and on-site diagnostics. During laboratory experiment dielectric loss values were investigated at different temperatures and different electrical field intensities for samples of oil-impregnated OI insulation characterized by different life consumption. Based on laboratory measurements results, a program was built; it can calculate the life consumption of paper oil-impregnated insulation by on-site dielectric loss measurements. Future life estimation is calculated based on the result of life consumption and thermal aging theory in the program. Thus the program can be used to qualify the degradation of oil-impregnated paper insulated cable, estimate the effect of operational history of the cable and support the future decisions of load profile and expected life of the cable.**

Keywords- dielectric loss, tanδ, serviced power cables, aging, oil-impregnated insulation, life consumption, future life estimation

I. INTRODUCTION

Dielectric loss measurement is a useful tool to assess the condition of oil-impregnated paper insulation [5, 6]. The condition of the oil-impregnated paper insulated cables can be determined by on-site diagnosis. In particular, dielectric loss (tanδ) can be measured in function of test voltage as the tanδ value indicates the condition of the OI insulation. To be able to determine the life consumption and future life estimation, a model is needed to relate dielectric loss in function of test voltage with life expectancy. By using the model, insulation life consumption can be calculated by tanδ values. On the other hand, thermal aging plays an important role in the aging process of a cable system. Thus in the model, the operational life consumption OLC due to the past load based on thermal ageing theory is also taken into account. It's known that for serviced aged the cable system, increase of load will accelerate the aging process even more. So future life estimation of the cable is calculated by future load. The model is based on the laboratory investigation of oil-impregnated paper insulation.

II. LABORATORY INVESTIGATION

The goals of the laboratory investigation into oil-impregnated insulation subjected to accelerate aging are:
to analyze the behavior of dielectric loss value of oil-impregnated paper insulation under different electrical and thermal stress; to analyze the behavior of dielectric loss value at certain applied voltage in function of life consumption, to analyze the behavior of dielectric loss difference between two applied voltage in function of life consumption; analyze the relative value in function of applied voltage and life consumption, by using information obtained in laboratory investigation, built a model which aim is to support maintenance decision regarding cables with oil-impregnated insulation.

In the laboratory, the tanδ values are measured by Schering Bridge. In figure 1, the setup of dielectric loss measurements is shown.

Figure 1. Test setup of dielecrtric loss measurements

The test object is oil-impregnated paper insulation. The test object is placed between the two electrodes. The normal configuration setup has two circular electrodes and a ring electrode around the low voltage electrode. Guard electrode eliminates surface leakage current which can affect the loss factor measurement. The set of these electrodes are placed in one of the arms of Schering bridge. In Figure 2, the electrodes are depicted.

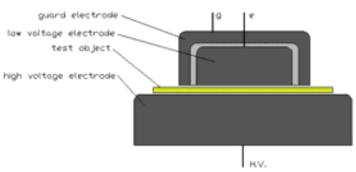

Figure 2. Cross section of the electrodes

The samples of oil-impregnated paper insulation are investigated; these samples are subjected to the accelerated aging in thermally controlled oven. The tests last for 225 days, and 40 samples are tested. The 40 samples are tested at different days between the 3^{rd} day and the 218^{th} day. Thus the

40 samples represent the 40 different percentage of life consumption of oil-impregnated paper insulation between 1% and 97% life consumption. The samples are subjected to different electrical stress from 0.7kV/mm to 6.1kV/mm and different thermal stresses from 25°C to 80°C.

A) Influence of electrical field intensity on tanδ value

During on-site diagnosis, dielectric loss value is measured at low temperature, so the influence of electrical field intensity on paper insulation at low temperature is important for the analysis the relation between dielectric loss value, voltage and life consumption.

The influence of electrical field intensity on paper insulation at low temperature can be deducted from the porous structure of paper. The conduction in impregnated paper can be described according to the motion of ions in oil [1]. When an electric field is applied, increasing applied field intensity enhances the ionic motion in the oil. The tanδ value exhibits a linear increase with applied voltage. This is caused by the fact that a rising applied field increasingly segregates the oppositely charged ions, which can be explained by atomic induced polarization. Aged paper insulation contains more pores and impurities, which increases tanδ dependence on electrical field.

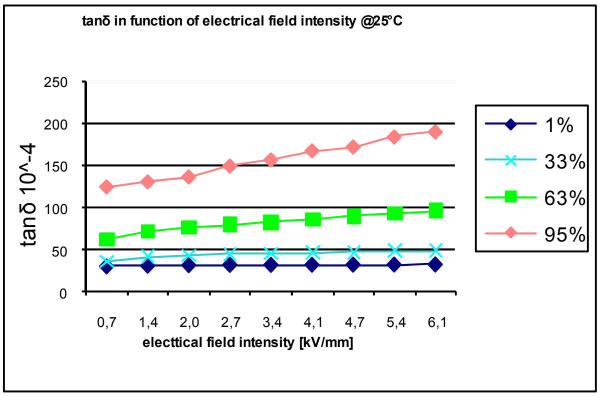

Figure 3. tanδ value in function of electrical field intensity at 25°C

In figure 2, the tanδ value in function of electrical field intensity is shown. Different lines indicate different life consumption. It can be seen that the tanδ value increases linearly with electrical field intensity; the increase becomes larger when the life consumption is higher.

B) Inflence of temperature on tanδ value

The influence of temperature on the insulation is due to the fact that oil viscosity decreases with temperature. When oil viscosity becomes lower, the ionic motion in the oil becomes higher; this causes the increase of dielectric loss [1]. When the paper insulation gets a higher degradation, there are more impurities which increase the oil conductivities even higher with the temperature. Thus the increase of dielectric loss becomes higher. In figure 3, the tanδ value in function of temperature at constant electrical field intensity is shown.

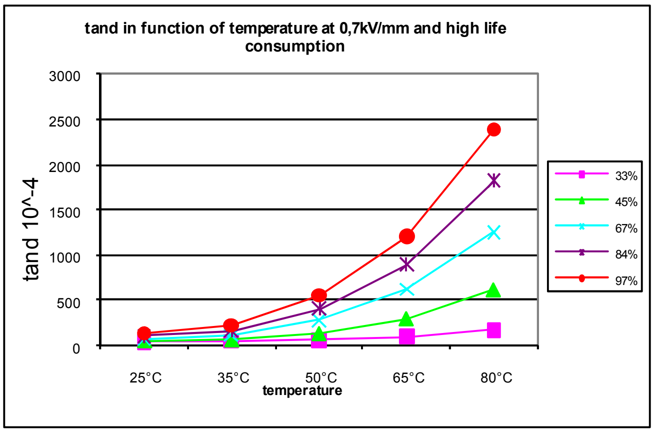

Figure 4. tanδ value in function of temperature at high life consumption

It can be seen that the tanδ increases rapidly with temperature. When the life consumption of the paper insulation is higher, the increase is larger.

III. DATA ANALYSIS

The data obtained during the experiment are analyzed to establish the relation between life consumption and the tanδ value at different applied voltage. This relation is needed to build a model for diagnosing life consumption and future life estimation of oil-impregnated paper insulated cable. In this analysis the electrical field intensity applied to the insulation samples during laboratory testing is transferred to per unit voltage value applied to the cable.

A) The relation between tanδ value, applied voltage and life consumption

In figure 4, the tanδ value in function of life consumption is shown, different color lines indicate different applied voltage. It can be seen that the tanδ value increases exponentially with life consumption. Moreover the increase is larger when the voltage applied to the insulation is larger.

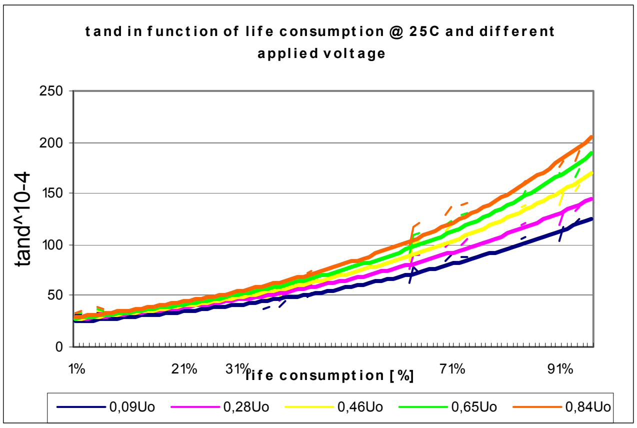

Figure 5. tanδ value in function of life consumption at 25°C and different life consumption

B) The relation between Δtanδ and life consuption

In figure 5, the relation between Δtanδ and life consumption is shown. During the test, the highest electrical field intensity applied on the samples is 6.1kV/mm, and the lowest one is 0.7kV/mm. When the electrical field intensity values are recalculated as voltage values applied on a cable, the two values are 0.84Uo and 0.09Uo. So in the Δtanδ value analysis, the voltages are chosen 0.84Uo and 0.09Uo. It can be seen that the Δtanδ value also increases exponentially with life consumption.

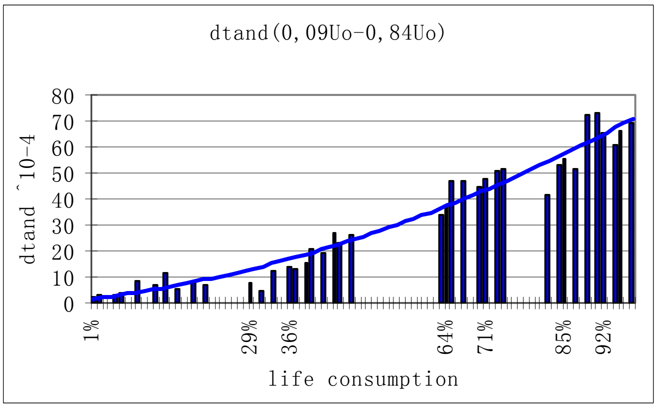

Figure 6. Δtanδ between 0.09Uo and 0.84Uo in function of life consumption at 25°C

C) The relation between relative tanδ value, voltage and life consumption.

From A and B, it is already known that Δtanδ and tanδ both change exponentially with life consumption. If Δtanδ is divided by tanδ, the relative tanδ value will change linearly with life consumption.

$$relative\_\tan\delta = \frac{\tan\delta(U2) - \tan\delta(U1)}{\tan\delta(U1)} \quad (1)$$

The reason for choosing relative tanδ value instead of Δtanδ is that the tanδ values obtained during laboratory investigation is different from the ones obtained during on-site diagnosis of the cable, but for relative tanδ value, the measurement value and real cable value are similar.

a) The relation between relative tanδ value and voltage difference

In figure 6, relative tanδ (U1=0.19Uo) value in function of applied voltage difference is shown. Different color lines indicate different life consumption of the insulation. It can be seen that the relative tanδ value increases linearly voltage difference. For more degraded paper insulation, the increase is bigger.

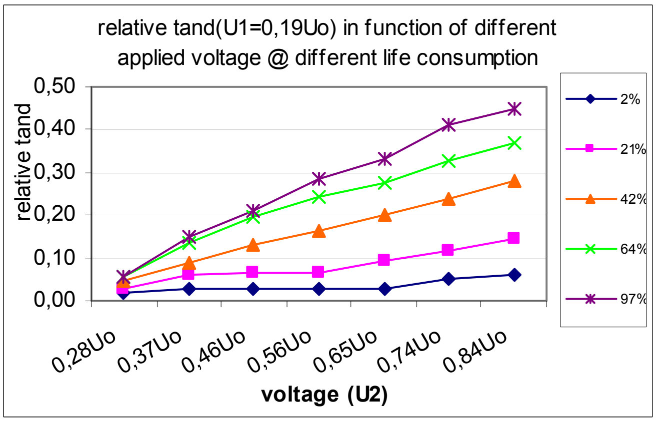

Figure 7. relative tanδ(U1=0.19Uo) in function of voltage difference at different life consumption

b) The relation between relative tanδ value and lower voltage U1

Figure 7 shows relative tanδ in function of lower voltage U1 when the voltage differences are the same. Different lines indicate different life consumption of the insulation. It can be seen that relative tanδ decreases with lower voltage U1. For higher life consumption the decrease is larger.

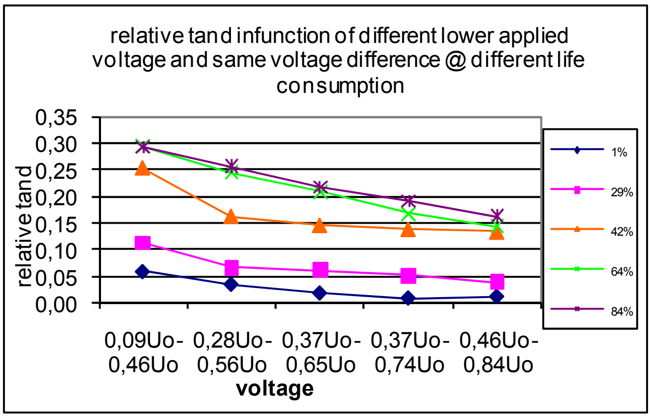

Figure 8. relative tanδ in function of different lower voltage and same voltage difference at different life consumption

Thus by using these results, a formula can be fitted to calculate life consumption by relative tanδ value:

$$ILC[\%] = 10 * \frac{0.09}{U_2 - U_1} * 1.1^{\frac{U_1}{0.09}} * \frac{\tan\delta(U_2) - \tan\delta(U_1)}{\tan\delta(U_1)} \quad (2)$$

It can be seen that relative tanδ value has a linear relation with life consumption, and the steepness of the linear equation depends on the voltage difference and lower voltage U1. So by using this formula, inputting two different voltage values U1 and U2 (U2>U1) and two tanδ values, the life consumption (Insulation Life Consumption ILC) can be calculated.

IV. LIFE CONSUMPTION AND FUTURE LIFE ESTIMATION MODELING

As introduced in the last chapter, the relative tanδ value changes linearly with voltage and life consumption. Thus, the relative tanδ value which is measured at low temperature during on-site diagnosis, is a useful tool to assess the life consumption of oil-impregnated paper insulation. A second method to diagnose the life consumption of the insulation is based on thermal aging and Arrhenius Law (Operational Life Consumption OLC). The future life estimation is based on both thermal aging and the result of life consumption calculated by relative tanδ value. The two calculations of life consumption should take different weights to be combined together. Figure 8 shows the flow chart of the whole program.

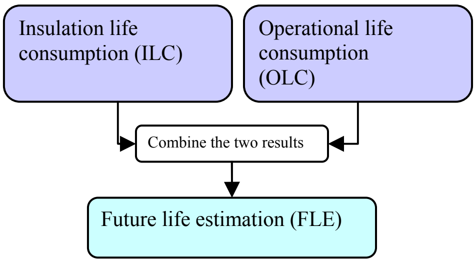

Figure 9. Flow chat of life consumption and future life estimation calculation

A) Insulation life consumption (ILC) calculation

In figure 9, the flowchart of program of ILC calculation by relative tanδ value is shown. Test voltages U1 and U2 are inputted into the insulation life consumption calculation formula. Values of tanδ(U1) and tanδ(U2) are inputted in the calculation of relative tanδ value, after that the result of relative tanδ value is inputted into the insulation life consumption calculation formula. The output is the percentage of insulation life consumption.

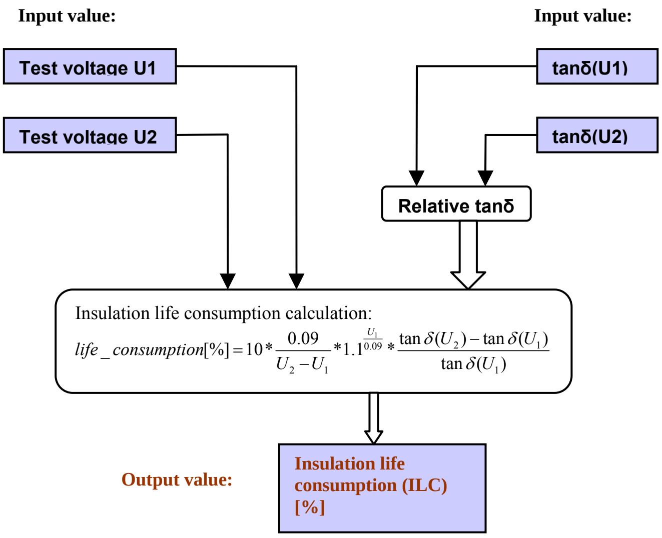

Figure 10. Flow chart of ILC calculated by relative tanδ value

In figure 10, the interface of ILC calculation program in excel is shown. The upper row shows the two input voltage values, U1 and U2 in per unit value. The lower row shows the two input tanδ values, tanδ(U1) and tanδ(U2) and the output insulation life consumption value.

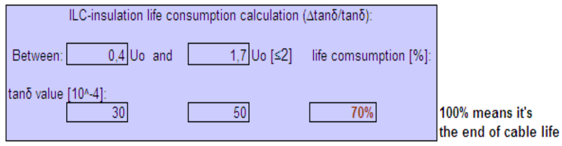

Figure 11. the interface of ILC calculation program

B) Operational life consumption (OLC) calculation

The operational life consumption calculated by past load is based on the Arrhenius law. Insulation degradation due to the load can be regarded as a thermal aging process [3]. Arrhenius law describes the relation between temperature and degradation rate, which shows that the temperature has an exponential influence on the degradation rate of the insulation. The Arrhenius Law is shown below:

$$k = A \cdot e^{(-Ea/R \cdot T)} \tag{3}$$

Where:
k is the reaction rate coefficient,
A is constant (maximum speed reaction),
Ea is the activation energy (energy that has to be delivered to start the reaction),
R.T is the average energy the molecule has at certain temperature,
R is the molecule gas constant (8,314472 [J $K^{-1}mol^{-1}$],
T is the absolute temperature.

The law of Monstsinger describes that at a certain temperature the degradation rate will be doubled, thus the parameters of calculating the degradation rate of oil-impregnated paper insulated cable can be determined by Monstsinger law. [3]. The formula of Monstsinger is shown below:

$$D_{year} = D_{to} * 2^{(\frac{T_{conductor} - 15}{T_d})} \tag{4}$$

Where:
D_{year} is yearly degradation,
D_{to} is degradation rate at 15°C,
T_d is temperature difference to get double degradation,
$T_{conductor}$ is cable temperature

According to the Monstsinger law, the parameters between temperature and degradation rate depend on the temperature increase to obtain degradation (T_d) and degradation rate at 15°C (D_{to}). For different kinds of insulation, the two parameters are different. In table I, typical D_{to} and T_d values of external gas-pressured mineral oil cable, external gas-pressured synthetic oil cable and paper insulated lead covered cable [4].

- TYPCAL I $T_{D,}$ D_{TO} AND T_{MAX} VALUES OF DIFFERENT TYPES OF CABLES

Cable types	T_d	D_{to}	T_{max}
External gas-pressure mineral oil cable	13°C	1%	60°C
External gas-pressure synthetic oil cable	21°C	1%	85°C
Paper insulated lead covered (PILC) cable	6,5°C	0,5%	43°C

The cable temperature ($T_{conductor}$) can be calculated from load applied on the cable. The formula is shown below [4]:

$$T_{conductor} = T_{ground} + (T_{\max} - T_{ground}) * (load\%)^2 \qquad (5)$$

T_{max} is the maximum operational temperature for the cable. The maximum temperature is different for different types of cable. Table 1 shows the maximum temperature for different types of cables.

Figure 11 shows the flow chart of operational life consumption calculated by past load. Percentage of load, ground temperature and cable maximum operational temperature are inputted into the cable temperature calculation. Then the result of cable temperature, T_d and D_{to} values are inputted into the calculation of yearly degradation of the cable. After that, the result of yearly degradation of cable and cable age are inputted into the OLC calculation.

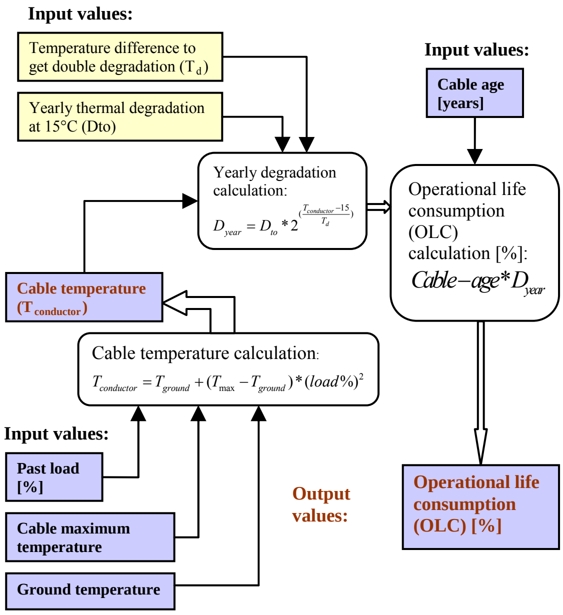

Figure 12. Flow chart of OLC calculation by past load

In Figure 12, the interface of operational life consumption calculation in excel is shown. T_d and D_{to} are the input values. The values are based on the types of cable. The values of three different types of cable are shown in the figure. Below that, it is shown that when T_{ground}, T_{max}, percentage of past load and cable age are input values, the results are $T_{condutor}$ and operational life consumption.

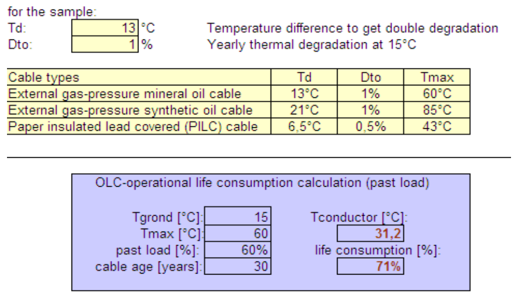

Figure 13. the interface of OLC calculation by past load

C) *Total life consumption (TLC) calculation*

The future life estimation calculation is based on the result of ILC and OLC. So first, the two results of life consumption calculated by different methods should be combined together. By combination of the two results total life consumption (TLC) is obtained. In figure 13, the two results of life consumption calculation are combined together using different weights for better accuracy. The phases U, V and W represent the three phases of a cable. During the life consumption calculation, the three phases are all taken into account. The ILC results of the three phases are compared, if the difference is smaller than 3%, ILC takes 50% weight, and OLC takes 50% weight; If the difference is larger than 3% and smaller than 5%, ILC takes 60% weight, and OLC takes 40% weight; If the difference is larger than 5%, ILC takes 70% weight, and OLC takes 30% weight. So the total life consumption value depends on the difference of ILC value between each phase.

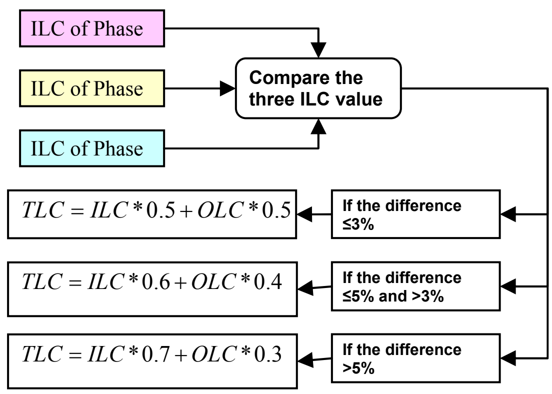

Figure 14. Flow chart of total life consumption (TLC) calculation

D) *Future life estimation(FLE) calculation*

The calculation of future life estimation is based on total life consumption and thermal aging. Figure 14 shows the flow chart of calculation of future life estimation. Until the calculation of yearly degradation, the procedure is similar to the life consumption calculation by past load, only now the future applied load should be taken instead of past load value. After that, the result of total life consumption is inputted. The output value, future life estimation, is based on the percentage of total life consumption and yearly degradation.

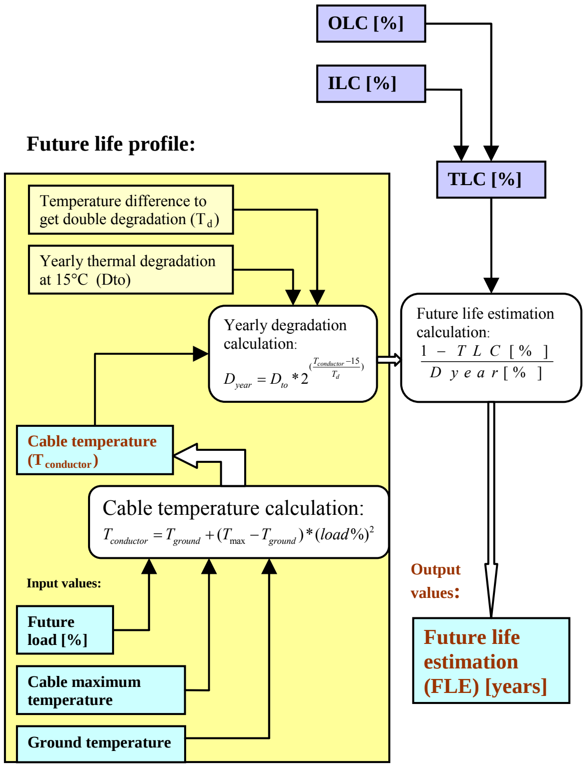

Figure 15. Flow chart of FLE calculation

Figure 15 shows the interface of future life estimation calculation program in excel. The temperature difference of doubling degradation (T_d), degradation rate at 15°C and cable maximum value are the same as OLC calculation. The input values are ground temperature and future load. The output values are: cable temperature ($T_{conductor}$), yearly degradation rate (D_{year}) and future life estimation in years.

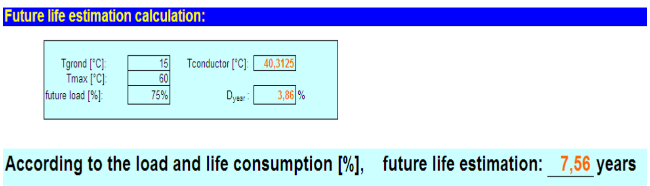

Figure 16. the interface of FLE calculation program

V. CONCLUSIONS

Based on the laboratory investigation, a model is built to calculate insulation life consumption (ILC) by relative tanδ value. The operational life consumption (OLC) calculated by thermal aging is also taken into account in the model. The total life consumption is based on the ILC and OLC results. The future life estimation (FLE) is based on the TLC and thermal aging. The model can be concluded as:

The ILC calculation depends on the tanδ value of the cable insulation.

The OLC calculation depends on the operational history: ground temperature, past load, cable age and cable type.

ILC and OLC can be calculated independent from each other.

The total life consumption combines ILC and OLC values.

The future life estimation depends on the TLC and future load.

The ILC calculation in the model helps to qualify the level of insulation degradation of a particular oil-impregnated paper cable circuit.

Based on OLC calculation in the model, the effect of operational history and thermal aging can be estimated.

Using the FLE calculation, future decisions about the permissible load profile and expected life-time can be supported.

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