EVALUATION OF POWER TRANSFORMER INSULATION THROUGH MEASUREMENT OF DIELECTRIC CHARACTERISTICS

Victor V. Sokolov and Boris V. Vanin
ZTZ-Service Company

INTRODUCTION

This paper summarizes our experience with the evaluation of the insulation condition and the identification of defects in spaces of the main insulation of power transformers. Specifically, this evaluation is based on the dissipation factor, capacitance and DC insulation resistance measured on core-type large power transformers with oil-barrier insulation systems. The following topics will also be discussed: typical defects in the insulation spaces and their influence on the dielectric characteristics; the effect of water and temperature on the dielectric characteristics of the insulation system; the estimation of the average water content in the pressboard; the evaluation of contamination in the oil spaces and on the insulation surface. Case studies of in-service transformers will be included.

An intelligent assessment of power transformer serviceability requires thorough knowledge of the actual condition of the unit. This information is also essential to determine the life-extension program for aging equipment. One of the main life limiting factors is the reduction of the dielectric strength in the spaces of the main insulation, which is caused by an accumulation of moisture and aging contaminants, and a deterioration of insulation due to partial discharge activity. Our experience has shown that about 30% of the large power transformer failures, after 15-20 years of operation, occur due to a breakdown of insulation[1]. There is convincing evidence that the insulation system works as an effective filter which tries to clean the oil from the aging products and water.

We have found that a dramatic reduction in the dielectric strength of the oil-barrier insulation system may occur under conditions where the measured characteristics of the oil meet all the traditional criteria.

TYPICAL DEFECTS IN SPACES OF MAIN INSULATION

Classification of Defects

The following typical defects in the transformer insulation system can be identified:

- General moistening of the cellulose insulation. The major part of water is concentrated in the "thin" Insulation, namely the pressboard barriers[2].
- Oil contamination with water, conducting particles and aging products.
- Insulation surface contamination due to:
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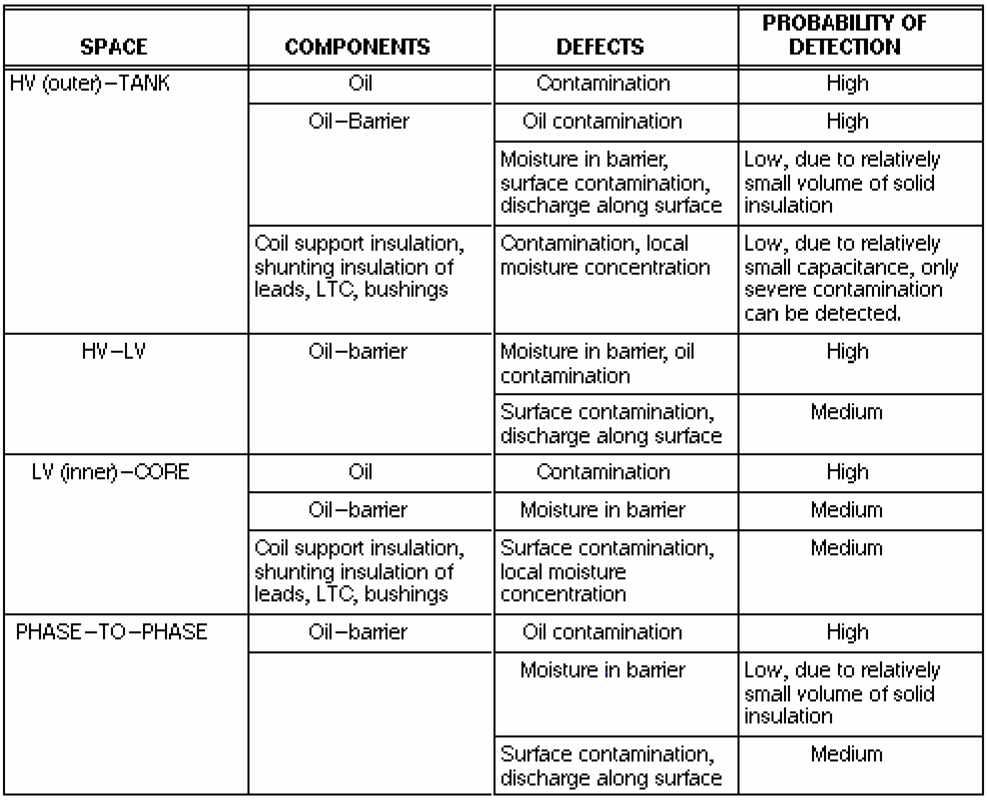
  - an adsorption of oil aging products by the surface of the solid insulation
  - a deposit of insoluble aging products in areas of high electrical stress[3]
  - a deposit of conducting particles in areas of high electrical stress[4].

The above defects usually fall into the category of reversible defects. The damage created by partial discharge activities is usually irreversible. This type of damage usually has a form of carbonized tracks (creeping trees) that extend between the electrodes along the surfaces[5]. The most common defects are summarized in Table I.

TABLE I
TYPICAL DEFECTS AND DIAGNOSTIC POSSIBILITIES IN THE MAIN INSULATION



SPACE	COMPONENTS	DEFECTS	PROBABILITY OF DETECTION
HV (outer)–TANK	Oil	Contamination	High
	Oil–Barrier	Oil contamination	High
		Moisture in barrier, surface contamination, discharge along surface	Low, due to relatively small volume of solid insulation
	Coil support insulation, shunting insulation of leads, LTC, bushings	Contamination, local moisture concentration	Low, due to relatively small capacitance, only severe contamination can be detected.
HV–LV	Oil–barrier	Moisture in barrier, oil contamination	High
		Surface contamination, discharge along surface	Medium
LV (inner)–CORE	Oil	Contamination	High
	Oil–barrier	Moisture in barrier	Medium
	Coil support insulation, shunting insulation of leads, LTC, bushings	Surface contamination, local moisture concentration	Medium
PHASE–TO–PHASE	Oil–barrier	Oil contamination	High
		Moisture in barrier	Low, due to relatively small volume of solid insulation
		Surface contamination, discharge along surface	Medium

Distribution of Defects

Transformer insulation is a composite dielectric system, located between the electrodes, i.e., winding conductors, and grounded parts of the transformer. Dielectric measurements allow us to determine the partial conductance of the dielectric system between each accessible pair of electrodes. Sometimes the measured value is equal to the conductance of the insulation zone between electrodes. For instance, in the zone between the high-voltage (HV) winding (outer) and the tank, all the current from the HV winding flows to ground. Sometimes the measured value is not equal to the conductance of the insulation zone. For example, in the interwinding space, in case of a severe contamination of the barrier surface, the portion of current between the HV winding and the low-voltage (LV) winding flows down to the ground along the surface of the barrier, resulting in a decrease of the measured dissipation factor.

Let us consider the possibilities for diagnosis using a two-winding transformer as an example. The most important components of the main transformer insulation are:
- Insulation between the HV winding and the tank, including the HV bushings
- Insulation between the HV and the LV windings
- Interphase insulation

These components usually have the smallest margin of the dielectric strength, and, as a result, are the most sensitive to the insulation deterioration. The monitoring of the solid and liquid insulation in these components, i. e., a monitoring of their dielectric characteristics, is a subject of great importance and is one of the main objectives of transformer diagnostic tests. In other areas of the insulation, specifically the insulation between the LV winding and the core, the margin of dielectric strength is usuallys ignificantly higher than in the spaces that include HV winding. Therefore, only a very high degree of deterioration is usually cause for concern.

In a two-winding transformer there are three main pairs of electrodes which allow measurements three corresponding insulation zones: HV-TANK, HV-LV, and LV-CORE. Sometimes interphase insulation is also accessible for testing. The typical defects in the insulation spaces and the possibilities for a diagnostic analysis are summarized in Table I. The simplified view of the various insulation spaces, the equivalent circuit of the measured conductance, and the corresponding equations are presented in Appendix 1.

The typical components of the space HV-TANK (Appendix 1, Table I-1) are: the oil, oil-pressboard space, coil support insulation (situated between the bottom or top turn and the ground), high-voltage bushings and shunting insulation of leads, LTC, etc. The main part of this insulation space is the oil. This insulation zone presents a good opportunity to identify the condition of the oil. In this space the barrier insulation has the highest probability of adsorbing water or being contaminated. However, the influence of the barrier condition on the overall dielectric characteristics of this space is usually minor. The relatively small capacitance of the coil support insulation, bushings and shunting insulation components allows us to detect only severe defects in these components. Thus, the main goal of the measurements in the zone HV-TANK is to determine the condition of the oil and to detect severe defects in the other components.

The interwinding space includes one component: oil-pressboard space (Appendix 1, Table II-1). The composition of the space allows us to detect and identify the condition of the pressboard barriers as well as of the oil. This is the only space where one can practically estimate water content in the pressboard.

The typical components of the LV-CORE space (Appendix 1, Table III-1) are: oil-pressboard space, coil support insulation, shunting insulation of the leads, LTC, LV bushings, etc. This space is the least useful in evaluating the condition of the solid insulation. The main goal of the measurements in the space LV-CORE is the detection of severe surface contamination or significant local moisture concentration in the insulation components, etc.

In the phase-to-phase space, the solid insulation is often the smallest contributor to the measurement which allows us to evaluate the condition of the oil. However, due to the small capacitance of the space, it is sometimes possible to detect the surface contamination of the barrier or the discharge along the barrier.

EFFECT OF TYPICAL DEFECTS ON DIELECTRIC CHARACTERISTICS

Water in Cellulose Insulation

Water in cellulose insulation is found in two forms:
- vapor that moves freely within micropores of cellulose material (unboundwater)
- adsorbed water molecules moving in the vicinity of active centers of cellulose molecules.

The source for the insulation conductivity is the presence of impurity ions. The movement of the ions increases with increase of the temperature. The active centers of cellulose molecules "attract" the ion impurities and by doing so they "restrict" their movement.

Adsorbed water molecules, being polarized, "pull the ions away from the active centers of cellulose molecules. It can be said that they shield the effect of the cellulose molecules, thus facilitating the ion movement. This increases the conductivity and the dissipation factor. When the overall water content in the cellulose is low the temperature increase causes a redistribution of water. This results in a decrease of adsorbed water and increase of the vapor. Reduction of the adsorbed water diminishes the shielding effect it has on the active centers of cellulose molecules, slows down the movement of ions and, consequently, reduces the conductivity of the cellulose. Further increase in temperature increases the movement of the ions, resulting in increase in conductivity and dissipation factor. This is the origin of the "U-shape relationship" between the dissipation factor and the temperature (Figure 1)[6]. These U-shape graphs should be recognized as a criterion of dry insulation. With the water content above 1%, the dissipation factor and conductivity versus the temperature and moisture can be approximated as exponent functions.

Dissipation Factor Characteristics of Oil-Impregnated Cellulose
FIGURE 1
(For figure 1, refer to the 1996 Book, page 8-7.4).

Pressboard Contamination and Surface Partial Discharge

Contamination of the pressboard with the by-products of oil aging leads to an increase of the dissipation factor. Temperature plays an important role in this relationship (Figure 2).

Dissipation Factor Characteristics of Oil-Impregnated Aged Cellulose
FIGURE 2
(For figure 2, refer to the 1996 Book, page 8-7.4).

A phenomenon known as "creeping discharge" occurs in the composite insulation of the transformer. It progresses in four steps, resulting in a fifth: a powerful arc within a transformer, if the unit is not removed from service on time. These steps are:

1. Breakdown of an oil gap between the transformer winding and the nearest barrier.
2. Sliding discharge in oil along the barrier.
3. Oil and water being forced out of the pressboard surface pores in the vicinity of the sliding discharge, creating a microscopic sparking within the pressboard.
4. Sparking splitting oil molecules, forming hydrocarbons (acetylene among them) which become pure carbon; carbon forming conducting paths in the pressboard. This process continues until the treeing conducting paths cause shunting of nonequipotential parts in the transformer. The time period in which this process takes place can be from minutes to months.

If the unit is taken out of service before the fatal fifth stage, the existence of carbonized traces may sometimes be detected by the dielectric measurements. Typically, the temperature influence on the dielectric characteristics is diminished in the presence of carbonized traces.

Temperature Effect on Clean and Contaminated Oil

The accumulation of contaminants in oil changes the conductivity and dissipation factor as well as their temperature coefficient. The dissipation factor and conductivity have similar temperature dependence characteristics. Temperature dependence for clean oil can be approximated as an exponential function (Figure 3).

Dissipation Factor Characteristics of Oil
FIGURE 3
(For figure 3, refer to the 1996 Book, page 8-7.5).

Oil contaminated with particles or colloid sometimes has a reduced temperature coefficient at an elevated temperature due to the phenomena of "self-cleaning." Moist oil (compared to clean oil) has a reduced temperature coefficient due to the increase of oil relative saturation at lower temperatures and a corresponding increase of oil conduction. The dielectric permittivity of oil is slightly reduced with the change in temperature. The accumulation of polar products leads to an increasing oil permittivity. All these have an effect on the dielectric characteristics of the oil-barrier insulation in the transformer

DIELECTRIC CHARACTERISTICS OF DEFECT-FREE INSULATION

Characteristics of Solid Insulation

Undamaged, dry, and clean oil-impregnated insulation usually exhibits the following characteristics:

- Water content in the barrier is 0.5 - 1.0% or less.
- A dry and clean surface.
- No irreversible damage due to partial discharge activity.
- A dissipation factor for solid insulation from 20°C to 70°C is less than 0.5%
- Insulation dc conductivity at 20°C on the order of $\gamma_{20} = 2.5 \cdot 10^{-13}$ Ohm^{-1} m^{-1} and increasing with temperature exponentially as $\gamma_t = \gamma_{20} \cdot \mathbf{e}^{\alpha (t-20)}$, where α is usually 0.05.
- A practically constant dielectric permittivity of the pressboard, typically: $\varepsilon_p = 4.5$.

Characteristics of Oil

Unaged, clean, and dry oil usually exhibits the following characteristics:

- From 60°C to 70°C the water content is 10 - 15 ppm or less.
- At 90°C the dissipation factor ($\tan \delta_0$) is 0.5% or less.
- At lower temperatures up to 89°C, $\tan \delta_0$ decreases exponentially as $\mathbf{tan}\ \delta_{0t} = \mathbf{tan}\ \delta_{0\,90} \cdot \mathbf{e}^{-\beta (90-t)}$, where β is usually 0.04.
- Oil is practically non-polar and correspondingly: $\varepsilon_{20} - \mathbf{n}^2 < \mathbf{0.01}$, where ε_{20} is permittivity at 20°C and **n** is a refractive index.
- Neither the conducting (metal or coal) nor the nonconducting visible particles are present

EVALUATION OF INSULATION CONDITION THROUGH MEASUREMENT OF DIELECTRIC CHARACTERISTICS

Capacitance of Insulation Space

The magnitude of capacitance should remain practically unchanged, being slightly decreased when the temperature increases due to the decrease of the oil dielectric permittivity, particularly, in the HV-TANK space.

Space HV-TANK

Dissipation factor and dc insulation resistance of composite insulation in the HV-TANK space are influenced predominantly by the condition of the oil. If the dissipation factor of the solid insulation is 0.5% or less, using (4B) and (7B) (see Appendix 2), the equivalent dissipation factor tanδ* of the HV-TANK space without the bushings (see Table I-A in Appendix 1) can be expressed as follows:

$$\tan\delta^*_{HV\text{-}T} \sim K_0 \tan\delta_0 + 0.5(1K_0) \quad (1)$$

where $K_0 \sim 0.4...0.6$ for the core-form units, and $\tan\delta_0$ is the measured dissipation factor of the oil sample corrected to the same temperature as $\tan\delta^*_{HV\text{-}T}$. Thus, for the oil that has $\tan\delta_0 < 0.5\%$ at 90°C, the defect-free composite insulation has $\tan\delta^*_{HV\text{-}T} < 0.5\%$ in the range of temperatures 20...70°C[7]. If the dissipation factor of dry solid insulation components is assumed to be constant, the difference between the two magnitudes of $\tan\delta^*_{HV\text{-}T}$ tested at two different temperatures ($t_2 > t_1$) allows us to estimate the value of the oil dissipation factor in the space HV-TANK as follows:

$$\tan\delta^*_{HV\text{-}T(t2)} - \tan\delta^*_{HV\text{-}T(t1)} = K_0(\tan\delta_{0(t2)} - \tan\delta_{0(t1)}) \quad (2)$$

We assume that

$$\tan\delta^*_{0(t1)} = \tan\delta^*_{0(t2)} \cdot e^{-0.04(t2-t1)} \quad (3)$$

This results in the dissipation factor for the oil at the higher temperature t_2:

$$\tan\delta_{0(t2)} = [\tan\delta^*_{HV\text{-}T(t2)} - \tan\delta^*_{HV\text{-}T(t1)}] / K_0 [1 - e^{-0.04(t2-t1)}] \quad (4)$$

The minimum value of the dc insulation resistance of the HV-TANK space should be more than the insulation resistance of the oil space:

$$R_{HV\text{-}T(min)} > 1/(2\pi\, f\, C_0 \tan\delta_0) \quad (5)$$

where f is frequency, C_0 is capacitance of the oil space, and $\tan\delta_0$ is the measured dissipation factor of the oil sample tested at the same temperature as $R_{HV\text{-}T}$. Practically, the C_0 is determined by subtracting the measured capacitance of the HV bushings and estimated capacitance of the HV winding support insulation from the $C_{HV\text{-}T}$. If this information is not known, it can be assumed $C_0 = 0.7 \cdot C_{HV\text{-}T}$.

Space HV-LV

The condition of the pressboard barriers should be evaluated in the interwinding space. In this space, the dissipation factor and dc insulation resistance are influenced by the condition of the pressboard barriers as well as the oil.

Using the equations (4B) and (7B) (see Appendix 2 and Table 11-A in Appendix 1), the dissipation factor of the HV-LV space can be expressed as follows:

$$\tan\delta_{HV-LV} = K_0 \tan\delta_0 + (1 - K_0) \tan\delta_p \quad (6)$$

where $K_0 \sim$ 0.4.. .0.6 and can be calculated for certain designs, $\tan\delta_0$ is the measured dissipation factor of the oil sample at the same temperature as $\tan\delta_{HV-LV}$, and $\tan\delta_p$, is the pressboard dissipation factor. The share of the oil in the HV-LV space is less than in the HV-TANK space. If $\tan\delta_p <$ 0.5% in the range of temperatures 20...70°C and $K_0 = 0.4$, the dissipation factor of the defect-free composite insulation should be

$$\tan\delta_{HV-LV} < 0.3 + 0.4 \tan\delta_0 \quad (7)$$

Thus for the oil that has $\tan\delta_0$ 0.5% at 90°C, the defect-free composite insulation has $\tan\delta^*_{HV-LV} <$ 0.5% in the range of temperatures 20...70°C.

The dc insulation resistance of the defect-free HV-LV space can vary over a wide range depending on conductivity or the dissipation factor of the oil. The R_{HV-LV} value can be determined as follows:

$$R^*_{HV-LV} = 1/\lambda^* \gamma_p \quad (8)$$

where γ_p is pressboard conductivity; and λ^* is a design parameter (see Appendix 2). The can be defined as follows:

$$\lambda^* = A[B + 1/(1 + \alpha)] \quad (9)$$

where A and B are the design parameters which can be found from the "core and coils" drawing, and α is the oil factor. The α is determined as follows:

$$\alpha = \alpha' / \tan\delta_{0(70)} \quad (10)$$

where α' is typically in the range of 0.1...0.4, and $\tan\delta_{0(70)}$ is the oil dissipation factor at 70°C.

Example: $A = 1000$, $B = 0.07$, $\alpha' = 0.25$, $\gamma_p = 2.5 \cdot 10^{-13}\ \mathrm{Ohm}^{-1}\ \mathrm{m}^{-1}$ @ 20°C. The dc resistance of the defect-free HV-LV space will be as follows: 5,500 Mohm @ $\tan\delta_0 = 0.5\%$ @ 70°C, 11,400 Mohm @ $\tan\delta_0 = 0.1\%$ @ 70°C, 57,140 Mohm when oil is drained.

The conductivity of the pressboard depends on its temperature and this relationship can be expressed as follows:

$$\gamma_{p(t1)} = \gamma_{p(20)} \cdot e^{-0.05(t1-20)} \quad (11)$$

For dry insulation at, for example, 60°C:

$$\gamma_{p(60)} = 2.5 \cdot 10^{-13} \cdot e^{-2} \sim 3.4 \cdot 10^{-12}\ \mathrm{Ohm}^{-1}\ \mathrm{m}^{-1}$$

Estimation of Water Content in the Pressboard Barrier

A typical program for evaluating the water content in a large power transformer consists of the following steps:

- The Water Heat Run Test[2]. This includes taking measurements of the water content in the oil after heating the unit by loading it.

- The estimation of the water content in pressboard insulation using dielectric characteristics.
- The direct determination of the water content in the pressboard sample (as a part of the Life Assessment program).

In this paper we will discuss the second step. To estimate the water content in the oil-barrier insulation we use the dissipation factor and the 60 second insulation resistance measured in the interwinding space. We recommend heating the unit with internal losses up to 60-70°C before the measurements, to enhance the effect of the water on the insulation characteristics. The sample of oil is tested simultaneously with the insulation tests to determine the dissipation factor and water content, and sometimes dc resistivity also.

Estimation of Water Content Using Dissipation Factor of HV-LV Space

The following algorithm is used to estimate the average water content in the pressboard barrier:

- Measure $\tan\delta_{HV\text{-}LV}$ at the elevated temperature
- Determine $\tan\delta_0$ at the same temperature. Usually we measure the dissipation factor of the oil at three or four temperature points to define the relationship between $\tan\delta_0$ and temperature.
- Define the design parameters K_p and K_0 (see Appendix 2). If the design parameters are unknown, one can assume: $K_0 = K_p = 0.5$.
- Calculate the value of the dissipation factor of the pressboard $\tan\delta_p$ as follows:

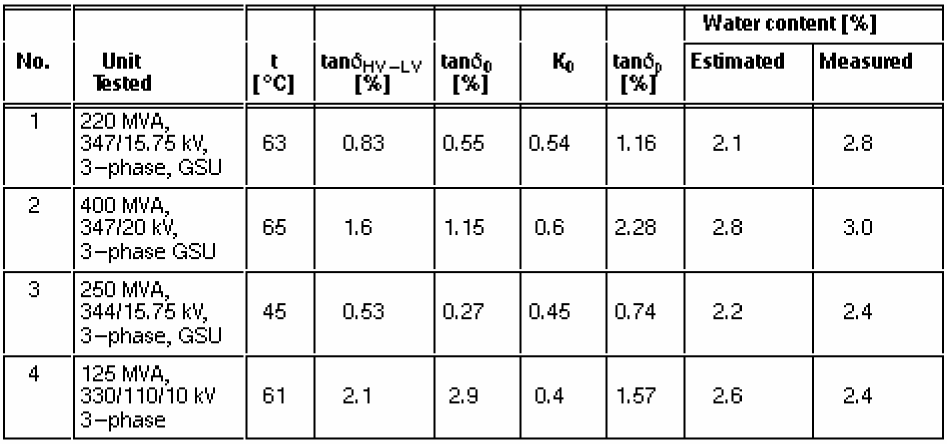
$$\tan\delta_p = (\tan\delta_{HV\text{-}LV} - K_0 \cdot \tan\delta_0)/K_p \quad (12)$$

- The water content can be determined by direct measurement of water content in the pressboard or by using equilibrium curves of the $\tan\delta_p$, and the water content in cellulosic materials at a given temperature. We have had good experience with analytical methods, but it can be more convenient to use equilibrium curves (Figure 1) presented by Griffin in Reference 6.

Examples of water content estimation using the measured dissipation factor are presented in the Table II. A good correlation between the estimated values and the results directly measured in the samples of the pressboard (after draining the oil) has been found.

TABLE II

EXAMPLES OF WATER CONTENT ESTIMATION IN BARRIER INSULATION THROUGH DISSIPATION FACTOR MEASUREMENTS



No.	Unit Tested	t [°C]	$\tan\delta_{HV-LV}$ [%]	$\tan\delta_0$ [%]	K_0	$\tan\delta_p$ [%]	Water content [%]	
							Estimated	Measured
1	220 MVA, 347/15.75 kV, 3-phase, GSU	63	0.83	0.55	0.54	1.16	2.1	2.8
2	400 MVA, 347/20 kV, 3-phase GSU	65	1.6	1.15	0.6	2.28	2.8	3.0
3	250 MVA, 344/15.75 kV, 3-phase, GSU	45	0.53	0.27	0.45	0.74	2.2	2.4
4	125 MVA, 330/110/10 kV 3-phase	61	2.1	2.9	0.4	1.57	2.6	2.4

The following observation can be made from Table II:

- The pressboard may have an elevated water content at a relatively small $\tan\delta_{HV-LV}$ if the $\tan\delta_0$ is very low.
- The pressboard may be fairly dry at an elevated $\tan\delta_{HV-LV}$, which is caused by an elevated $\tan\delta_0$.

In example 3, a low $\tan\delta_{HV-LV}$ = 0.53% at 45°C was measured. However, $\tan\delta_p$ was estimated at 0.74%, which corresponds to the water content of 2.2% (Figure 1). After draining the oil, the water content in the pressboard sample was tested at 2.4%.

Estimation of Water Content Using DC Insulation Resistance of HY-LV Space

The following algorithm is used to estimate the average water content in the pressboard barrier:

- Measure R_{HV-LV} at 60 sec in the HV-LV space at an elevated temperature.
- Measure the $\tan\delta_0$ of oil, usually at 70°C.
- Calculate the design parameter λ^* (see Appendix 2) as follows:

$$\lambda^* = A[B + 1/(1 + \alpha)] \quad (13)$$

If the design parameters are unknown, one can assume for approximate estimation the following quantities:

$\alpha = 0.25/\tan\delta_{0(70)}$, A = 1000 for a 3-phase unit and 500 for a 1-phase unit, B = 0.07

- Correct measured resistance R_{HV-LV} for the temperature as follows:

$$R_{HV-LV(20)} = R_{HV-LV(t)} \cdot e^{0.05(t-20)} \quad (14)$$

- Calculate the pressboard conductivity γ_p using equation:

$$\gamma_p = 1/\lambda^* R_{HV-LV(20)} \quad (15)$$

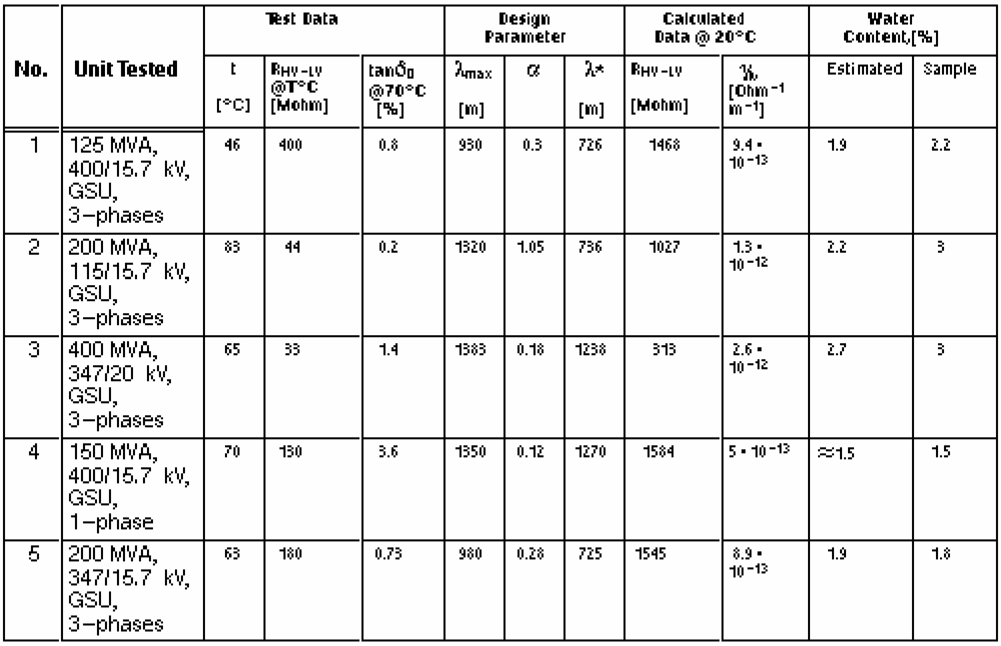
- Calculate the average water content W_p using equation:

$$W_p = (\ln \gamma_p / \gamma_0)/1.4 + 1.0 \quad (16)$$

where $\gamma_0 = 2.5 \cdot 10^{-13}$ Ohm$^{-1} \cdot$ m^{-1}. Examples of water content estimation using the measured dc insulation resistance are presented in Table III. Estimated values and the results directly measured in the samples of the pressboard (after draining the oil) correlate well.

TABLE III

EXAMPLES OF WATER CONTENT ESTIMATION IN BARRIER INSULATION THROUGH MEASUREMENTS OF DC INSULATION RESISTANCE



No.	Unit Tested	Test Data			Design Parameter			Calculated Data @ 20°C		Water Content,[%]	
		t [°C]	R_{HV-LV} @T°C [Mohm]	tanδ_0 @70°C [%]	λ_{max} [m]	α	λ^* [m]	R_{HV-LV} [Mohm]	γ_0 [Ohm^{-1} m^{-1}]	Estimated	Sample
1	125 MVA, 400/15.7 kV, GSU, 3–phases	46	400	0.8	930	0.3	726	1468	$9.4 \cdot 10^{-13}$	1.9	2.2
2	200 MVA, 115/15.7 kV, GSU, 3–phases	83	44	0.2	1320	1.05	736	1027	$1.3 \cdot 10^{-12}$	2.2	3
3	400 MVA, 347/20 kV, GSU, 3–phases	65	33	1.4	1383	0.18	1238	313	$2.6 \cdot 10^{-12}$	2.7	3
4	150 MVA, 400/15.7 kV, GSU, 1–phase	70	130	3.6	1350	0.12	1270	1584	$5 \cdot 10^{-13}$	≈1.5	1.5
5	200 MVA, 347/15.7 kV, GSU, 3–phases	63	180	0.73	980	0.28	725	1545	$8.9 \cdot 10^{-13}$	1.9	1.8

Estimation of Oil Contamination in Insulating Spaces

Experience has shown that in some cases the oil in the insulation spaces can be more contaminated than the oil in the sample taken from the bottom of the tank. The condition of the oil can be evaluated using the dissipation factor and dc insulation resistance measured in HV-TANK space, as it was discussed earlier. Examples of oil condition evaluation using the dissipation factor are presented in Table IV.

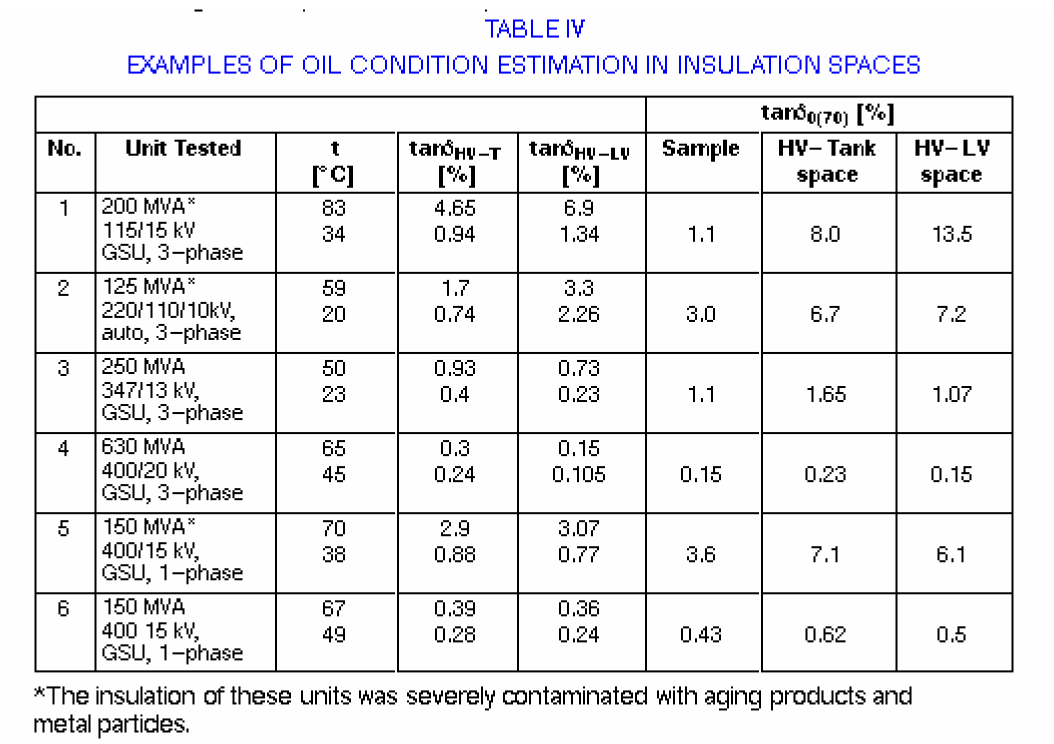


TABLE IV

EXAMPLES OF OIL CONDITION ESTIMATION IN INSULATION SPACES

					$\tan\delta_{0(70)}$ [%]		
No.	Unit Tested	t [°C]	$\tan\delta_{HV-T}$ [%]	$\tan\delta_{HV-LV}$ [%]	Sample	HV-Tank space	HV-LV space
1	200 MVA* 115/15 kV GSU, 3-phase	83 34	4.65 0.94	6.9 1.34	1.1	8.0	13.5
2	125 MVA* 220/110/10kV, auto, 3-phase	59 20	1.7 0.74	3.3 2.26	3.0	6.7	7.2
3	250 MVA 347/13 kV, GSU, 3-phase	50 23	0.93 0.4	0.73 0.23	1.1	1.65	1.07
4	630 MVA 400/20 kV, GSU, 3-phase	65 45	0.3 0.24	0.15 0.105	0.15	0.23	0.15
5	150 MVA* 400/15 kV, GSU, 1-phase	70 38	2.9 0.88	3.07 0.77	3.6	7.1	6.1
6	150 MVA 400 15 kV, GSU, 1-phase	67 49	0.39 0.28	0.36 0.24	0.43	0.62	0.5

*The insulation of these units was severely contaminated with aging products and metal particles.

Evaluation of Insulation Surface Contamination

The surface contamination of the insulation is evaluated using equation (2B) presented in Appendix 1:

$$\tan\delta_{HV-LV} = K_p \cdot \tan\delta_p + K_0 \cdot \tan\delta_0 + K_s \cdot \tan\delta_s$$

This equation presents the dissipation factor of the HV-LV space as a combination of three components. The first one represents the paper, the second the oil, and the third one the insulation surface. If the oil is drained the second component is not present. The difference between the $\tan\delta_{HV-LV}$ with and without the oil allows evaluation of the condition of the oil. Furthermore, assuming $\tan\delta_p = 0.5\%$ and using the $\tan\delta_{HV-LV}$ measured without the oil, we can evaluate the influence of the insulation surface.

Creeping Discharge on Barrier Insulation

One of the defects often found in the pressboard insulation is a creeping discharge on the surface, which has an appearance of carbonized traces. The presence of these traces sometimes may be detected by dielectric measurements in the HV-TANK or PHASE- TO-PHASE spaces. We have identified two types of discharge behavior. Each has a different effect on the measured dielectric characteristics.

1) Creeping discharge that does not extend to the ground: The presence of a carbonized trace may change the dissipation factor and the capacitance of the space. However, a noticeable change is observed only when the damaged portion is fairly large. As the discharge progresses, both the capacitance and the dissipation factor increase. The quantitative increase may be on the order of 0.1% and 1% correspondingly. The symptom of a creeping discharge may be a dissipation factor practically unchanging with raising the test temperature. An elevated dissipation factor in the localized area, i. e., in the HV-LV space of only one phase, may be considered as another sign of the damage present.

A typical example was our detection of the defect in the generator step-up unit 250 MVA, 330/15 kV. The measurements of the dissipation factor in the HV-LV space at 20°C resulted in the following data: Phase A - 0.2%; phase B - 0.25%; phase C - 2.9%. After raising the temperature to 40°C, the dissipation factor in phases A and B doubled. In phase C, however, the result was practically unchanged. The tear-down inspection revealed the presence of the creeping discharges on the barriers in the HV-LV space exposed to the HV winding.

2) Creeping discharge that extends to ground: When the creeping discharge extends to the ground, the damaged portion of the insulation extends beyond the tested space. This may result in the decrease or even in the negative value of the dissipation factor and the decrease of capacitance.

Contamination of Barrier Insulation

The effect of the electromagnetic field on conducting and polar particles in the oil results in deposits on the barrier surface. A typical example was our experience detecting a contaminated barrier surface in a 750 kV shunt reactor. In this case the partial conductance in the tested space was influenced by the presence of the leakage path turning along the barrier surface to ground. This resulted in a dissipation factor decrease as the conductivity of the surface increased. The equivalent circuit and the equations for the HV-TANK space in the reactor are included in Appendix 1, Table III-A. To identify the surface contamination, the following measurements were performed on the suspect phase C:

- A dissipation factor at several temperatures
- A dissipation factor without oil present The results of the measurements between the HV winding and the electrostatic shield are presented in Table V.

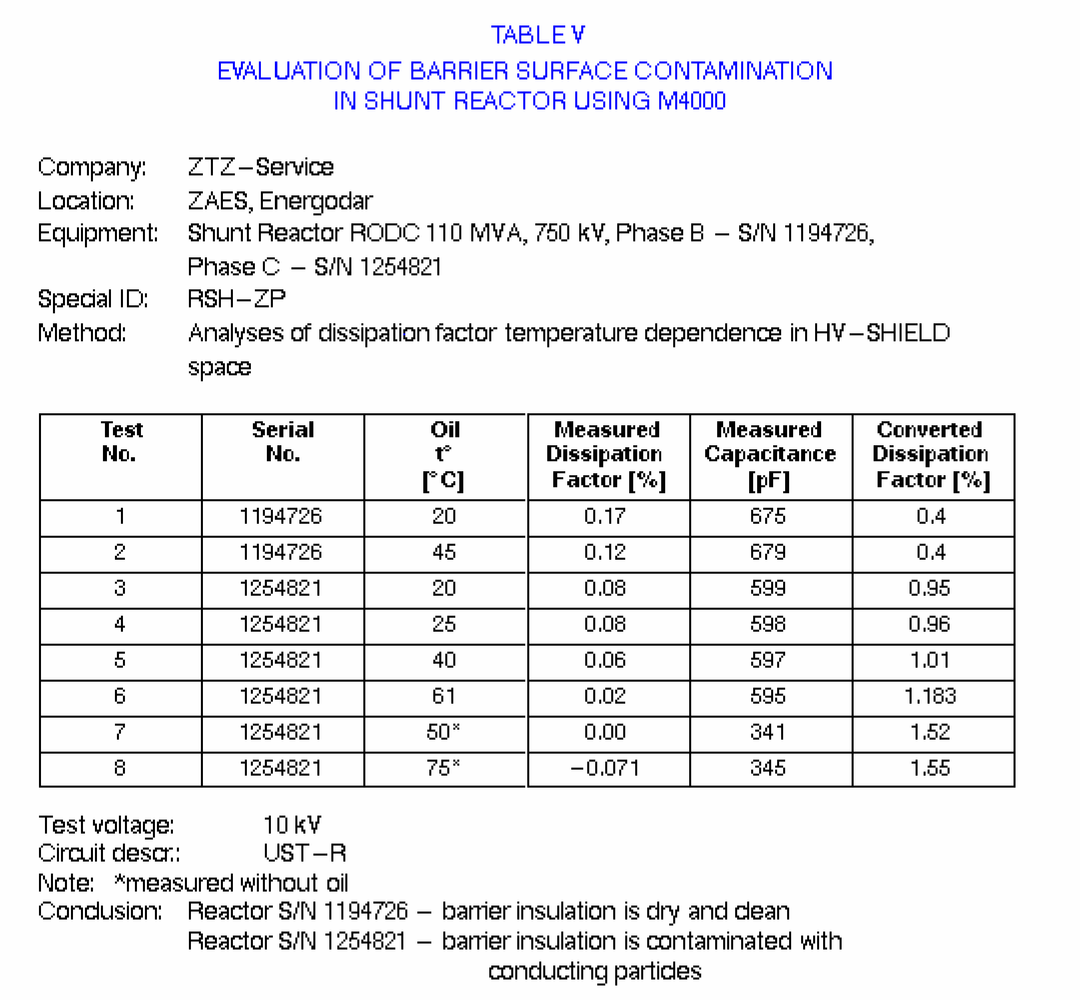


TABLE V

EVALUATION OF BARRIER SURFACE CONTAMINATION
IN SHUNT REACTOR USING M4000

Company: ZTZ–Service
Location: ZAES, Energodar
Equipment: Shunt Reactor RODC 110 MVA, 750 kV, Phase B – S/N 1194726,
Phase C – S/N 1254821
Special ID: RSH–ZP
Method: Analyses of dissipation factor temperature dependence in HV–SHIELD space

Test No.	Serial No.	Oil t° [°C]	Measured Dissipation Factor [%]	Measured Capacitance [pF]	Converted Dissipation Factor [%]
1	1194726	20	0.17	675	0.4
2	1194726	45	0.12	679	0.4
3	1254821	20	0.08	599	0.95
4	1254821	25	0.08	598	0.96
5	1254821	40	0.06	597	1.01
6	1254821	61	0.02	595	1.183
7	1254821	50*	0.00	341	1.52
8	1254821	75*	−0.071	345	1.55

Test voltage: 10 kV
Circuit descr.: UST–R
Note: *measured without oil
Conclusion: Reactor S/N 1194726 – barrier insulation is dry and clean
Reactor S/N 1254821 – barrier insulation is contaminated with conducting particles

Raising the temperature of the defective insulation led to the measured dissipation factor decrease (due to an increase of the leakage on the barrier surface). After the oil was drained, the dissipation factor decreased even further due to an increased sensitivity of the measurements to the condition of the solid insulation. The results of the measurements between the HV winding and the shield, between the shield and the ground, and between the HV winding and the ground were used to calculate the dissipation factor and the capacitance of the contaminated barrier. This is done though the conversion of the Delta equivalent circuit into Wye (see Table III-A in Appendix 1). The element representing the contaminated barrier is denoted as Y^*_1. Table V shows that as the temperature was increased, the "converted" dissipation factor increased, while the measured dissipation factor decreased. At the same time the good insulation in phase B showed no change in the converted results.

FACTORS INFLUENCING DIELECTRIC CHARACTERISTICS OF DEFECT-FREE INSULATION

Insulation Components with Inherently High Dielectric Losses

In some transformer designs, the insulation components subjected to a "low" electrical stress may have inherently high dielectric losses. The coil support insulation of the normally grounded neutral end of the winding may be an example of this component. These losses can mask problems in the main oil-barrier insulation space.

A typical example was the experience with a 400 kV shunt reactor after 22 years of service.

The analysis of insulation characteristics measured during the life of this unit showed that the dissipation factor of the HV-TANK space was around 1% and was practically stable. In that design the HV-TANK space is the only space accessible for the measurement. The coil support insulation installed between the winding and the ground was cause for the stable dissipation factor. The material used had inherently high losses. As a result, the change of the barrier insulation condition was completely masked. The design of the reactor was modified to make the grounding lead of the electrostatic shield externally accessible. The shield installed between the winding and the core allowed us to test the space between the winding and the shield using the UST circuit.

Core Ground Resistance

The general procedure to limit the current though the core ground is to use a resistor of 2...5 kohm in series with the grounding lead [8,9]. This resistor may drastically change the dissipation factor of insulation spaces. The test data presented in Table VI illustrates the influence of the grounding resistor on the dissipation factor of the tested insulation space.

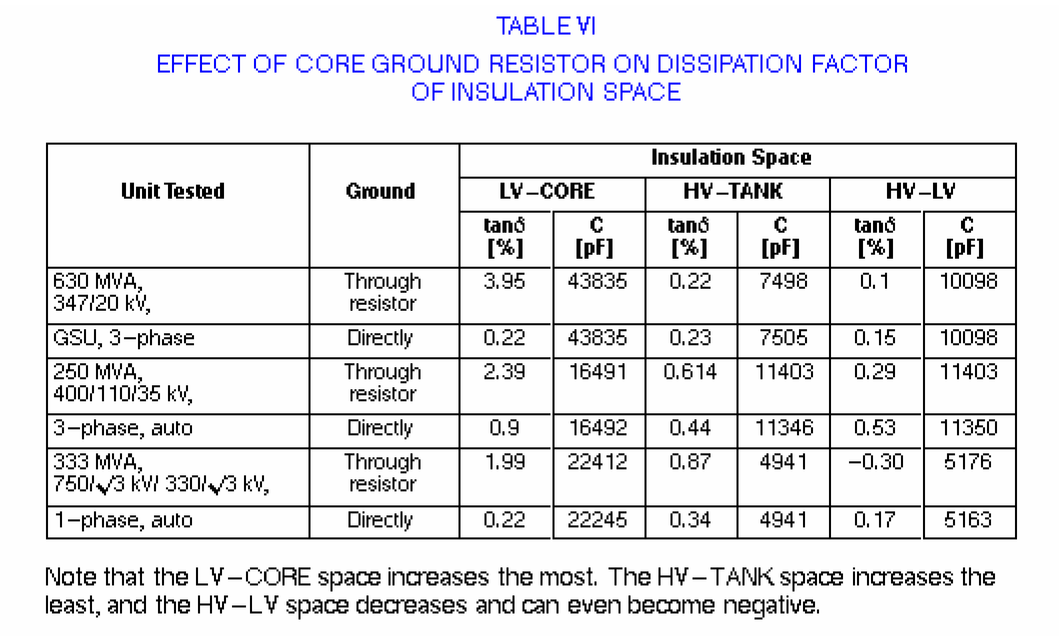


TABLE VI

EFFECT OF CORE GROUND RESISTOR ON DISSIPATION FACTOR OF INSULATION SPACE

Unit Tested	**Ground**	**Insulation Space**					
		LV–CORE		**HV–TANK**		**HV–LV**	
		tanδ [%]	**C [pF]**	**tanδ [%]**	**C [pF]**	**tanδ [%]**	**C [pF]**
630 MVA, 347/20 kV,	Through resistor	3.95	43835	0.22	7498	0.1	10098
GSU, 3–phase	Directly	0.22	43835	0.23	7505	0.15	10098
250 MVA, 400/110/35 kV,	Through resistor	2.39	16491	0.614	11403	0.29	11403
3–phase, auto	Directly	0.9	16492	0.44	11346	0.53	11350
333 MVA, 750/$\sqrt{3}$ kV/ 330/$\sqrt{3}$ kV,	Through resistor	1.99	22412	0.87	4941	–0.30	5176
1–phase, auto	Directly	0.22	22245	0.34	4941	0.17	5163

Note that the LV–CORE space increases the most. The HV–TANK space increases the least, and the HV–LV space decreases and can even become negative.

CONCLUSION

1. The deterioration of insulation due to an accumulation of water, particles and aging contaminants or due to irreversible damage of cellulose by a partial discharge results in the change of dielectric characteristics of the insulation components as well as of the insulation system. Diagnostic techniques can be improved on the basis of the measurements of capacitance, dissipation (or power) factor and dc insulation resistance, taking into account dielectric composition of the tested space and the relationship between the dielectric parameters of the tested space.

2. The dielectric parameters of defect-free insulation space can be defined as an equivalent characteristic of defect-free (dry, clean, unaged, undamaged) insulation components. The typical value of the dissipation (or power) factor of oil-barrier defect-free insulation should be, for instance, less than 0.5% over the range of temperatures from 20°C up to 70°C.

3. The average water content in the barriers and the oil condition in the insulation space can be estimated through the measurements of the dissipation factor and dc insulation resistance. Experience shows that the estimated and the actual condition of the insulation correlates well.

4. Defective insulation may cause an increase as well as a decrease of the measured dielectric parameters. In the special case of the barrier surface contamination, the dissipation factor of the interwinding space may decrease down to a negative value

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APPENDIX 1

TABLE I-1
EQUIVALENT CIRCUIT AND EQUATIONS FOR HV-TANK SPACE

(For Table I-1, refer to the 1996 Book, page 8-7.15).

TABLE II-1
EQUIVALENT CIRCUIT AND EQUATIONS FOR HV-LV SPACE

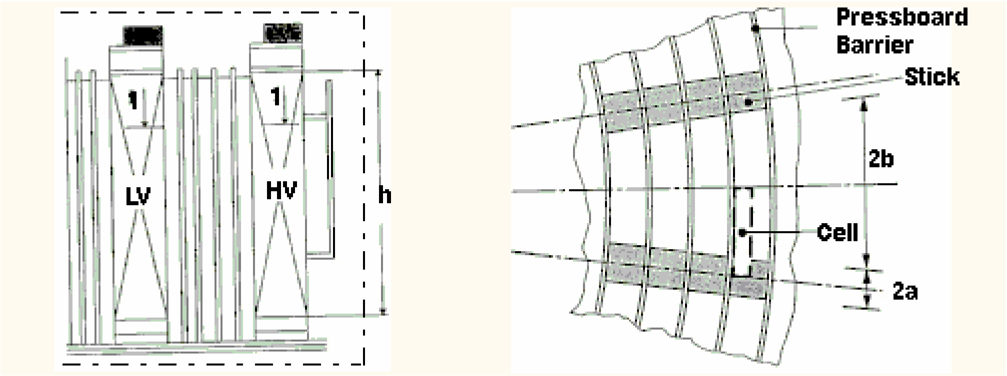
(For Table II-1, refer to the 1996 Book, page 8-7.16).

TABLE III-1
EQUIVALENT CIRCUIT AND EQUATIONS FOR LV CORE SPACE AND EXAMPLE WITH SHUNT REACTOR

(For Table III-1, refer to the 1996 Book, page 8-7.17).

APPENDIX 2
DIELECTRIC CHARACTERISTICS OF OIL-BARRIER HV-LV SPACE

A typical design of the oil-barrier insulation space is shown in Figure 1-2



a) Oil–Barrier HV–LV Space

b) Section of Oil–Barrier Insulation

FIGURE 1-2

We assume that the oil-barrier insulation consists of pressboard barriers ***n*** which are isolated by the oil gaps and are supported by the pressboard sticks to keep them apart. We also assume that the cellulose insulation is uniform and when the HV winding is energized, all the current flows to LV winding through the oil-barrier system. The insulation of the HV-LV space may be reduced to the following model (Figure 2-2).

Model of Oil-Barrier Insulation

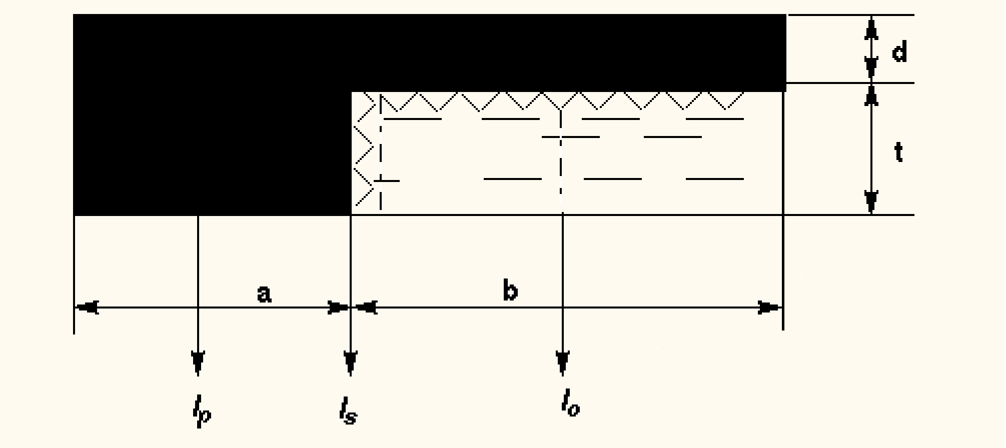


FIGURE 2-2

The total current through the model may be expressed as a sum of three components:

- Current through solid insulation I_P
- Current through oil I_0
- Current along the surface I_S

$$I_\Sigma = I_p + I_0 + I_s \quad (1\text{-}2)$$

This model allows us to determine the dissipation factor at the power frequency and the dc insulation resistance.

Dissipation Factor at Power Frequency

The equivalent dissipation factor of the interwinding space can be expressed as a sum of three components which represent dielectric losses in the pressboard, in the oil and on the surface:

$$\tan\delta_{HV\text{-}LV} = K_p \cdot \tan\delta_p + K_0 \cdot \tan\delta_0 + K_s \cdot \tan\delta_s \quad (2\text{-}2)$$

The design parameters K_p and K_0 can be expressed as follows:

$$K_0 = [m/(1 + m)] \cdot [v/(1 + v)] \quad (3\text{-}2)$$

$$K_p = 1 - K_0 \quad (4\text{-}2)$$

where

$$m = (b/a) \cdot [(t + d)/d] \cdot [1/(1 + v)] \quad (5\text{-}2)$$

$$v = (\varepsilon_p/\varepsilon_0) \cdot (t/d) \quad (6\text{-}2)$$

and ε_p and ε_0 are permittivities of the pressboard and oil, respectively.

The third component in (2-2) is of importance only when surface is severely contaminated, which allows for the following simplification:

$$\tan\delta_{HV\text{-}LV} = K_p \cdot \tan\delta_p + K_0 \cdot \tan\delta_0 \quad (7\text{-}2)$$

Typically, K_0 is in the range 0.4...0.6.

The temperature dependence of $\tan\delta_{HV\text{-}LV}$ is a result of the temperature effect on $\tan\delta_p$ and $\tan\delta_0$. If the solid insulation is dry, the first component in (7-2) can be considered constant and the change of the oil dissipation factor determines the change of $\tan\delta_{HV\text{-}LV}$. To define the condition of the pressboard it is necessary to measure the $\tan\delta_{HV\text{-}LV}$ and the $\tan\delta_0$ of the oil at the same temperature and then calculate $\tan\delta_p$ using expression (7-2)

DC Insulation Resistance

The mathematical analysis of the oil-barrier model (Fig. 2-2) has shown that the dc conductance of the interwinding space can be expressed as follows:
(8-2)

$$G_{HV*LV} = 1/R_{HV*LV} = (m * h)/(n + 2) * b/d\,[d/(t + d) * a/b) + 1/(1 + \alpha) + \alpha F/(1 + \alpha)]\gamma_p,$$

where h = height of the winding, m
m = number of the sticks
n = number of barriers b/d, d/(t+d),
a/b = ratios of the geometrical dimensions of the oil-barrier cell (Figure 2-2), which represent the relative volume of oil and solid insulation
γ_p = conductivity of the pressboard, ohm$^{-1} \cdot$ m^{-1}
α = parameter which determines the effect of oil conductivity γ_0
F = parameter which determines the effect of surface conductivity.

The components in the brackets express a particular effect of solid components, the oil and the surface of barrier on the dc conductance. Analysis has shown that the effect of surface conductivity is significant when the transformer is without oil, or if the oil is very clean. The latter can be explained as follows. Typically, the oil conductivity is significantly higher than the conductivity of the pressboard (paper). Therefore, the current flowing though the oil is higher than the current flowing on the surface of the pressboard.

However, when oil is very clean, such that $\gamma_0 \;\; \gamma_p$, the current though the oil is comparable with the current on the surface. In that case the measured dielectric characteristics can be more sensitive to the changes on the pressboard surface. In most cases, however, the effect of the surface conductivity on the insulation resistance can be overlooked.
The effect of the oil changes the insulation resistance within minimum and maximum values. The minimum value is as follows:

$$(9\text{-}2) \quad R_{HV-LV\,min} = 1/\,(\lambda_{max} * \gamma_p),$$

where

$$(10\text{-}2) \quad \lambda_{max} = m\,h/(n+2) \;*\; b/d\;(\,d/(t+d) * \;a/(b+1) = \mathbf{A(B+1)},$$

and

$$\mathbf{A = [mh/(n+2)] \cdot (b/d)}$$
$$\mathbf{B = \cdot\; (a/b)/(1 + t/d)}$$

The maximum value can be measured when the unit is without oil:

$$(11\text{-}2) \quad R_{HV-LV\,max} = 1/(\,\lambda_{min} * \gamma_p)\;,$$

where

$$(12\text{-}2) \quad \lambda_{min} = m\,h/(n+2) \;*\; a/(t+d) = \mathbf{A \cdot B}$$

for a given transformer both of these boundary values of dc insulation resistance depend only on cellulose conductivity. When oil is removed from the transformer the resistance of the HV-LV space should increase (typically by 10...25 times). The ratio of maximum and minimum values of insulation resistance depends on the relative volume of solid insulation and oil in the HV-LV space:

$$(13\text{-}2) \quad R_{max}\,/\,R_{min} = 1 + b\,/\,a * \;(t+d)/d$$

At the same conductivity of the insulation barrier the intermediate values between the minimum and maximum quantities of $R^*_{HV\text{-}LV}$ depend on the oil conductivity:

$$(14\text{-}2) \quad R^*_{HV\text{-}LV} = 1 * \lambda^* \,\gamma_p$$

where

$$(15\text{-}2)\; \lambda^* = m\,h/(n+2) * \;b/d\;[\,d/(t+d) * a/b \;+ 1/(1+\alpha)] \;= \mathbf{A[B + 1/(1+\alpha)]}$$

and

$$(16\text{-}2) \quad \alpha = t/d * \gamma_p/\gamma_0$$

The oil conductivity [ohm^{-1} · m^{-1}] can be expressed using the oil dissipation factor [%]:

$$\boldsymbol{\gamma_0 = \omega\, \varepsilon_0\, \varepsilon \tan\delta_0 = (2\,\pi\, f\, \varepsilon \tan\delta_0)/36\,\pi\, 10^{11} = (f\, \varepsilon \tan\delta_0)/1.8 \cdot 10^{12}} \quad (17\text{-}2)$$

Using f = 50 Hz and the oil dielectric constant $\varepsilon = 2.2$ results in the following:

$$\boldsymbol{\gamma_0 \sim 0.611 \cdot 10^{-10} \tan\delta_0}$$

Since we normally use the oil dissipation factor at 70°C, the pressboard conductivity [$\mathrm{ohm}^{-1}\ \mathrm{m}^{-1}$] at that temperature is as follows:

$$\boldsymbol{\gamma_{p70} = 2.5 \cdot 10^{-13}\, e^{0.05(70-20)} = 3.05 \cdot 10^{-12}}$$

Finally, using (16-2) α is expressed as follows:

$$\boldsymbol{\alpha = (t/d) \cdot (3.05 \cdot 10^{-12}/0.611 \cdot 10^{-10} \tan\delta_{0\ 70}) \sim (0.05t/d)/\tan\delta_{0\ 70}}$$

Typically, 0.05t/d = 0.1...0.4.

To determine the condition of the pressboard, it is necessary to measure the HV-LV dc resistance, to determine the design parameter λ^* calculated using the measured $\tan\delta_0$, and finally to calculate insulation conductivity γ_p using [14-2].