ABSTRACT

This paper discusses the typical defects and failure modes associated with high-voltage transformer bushings based upon experience gained from a large population of bushings as well as other studies of failures. Failure development considerations, defective condition determination, and defect images are presented. The discussion included in this paper covers failure modes caused by insulation deterioration, development of discharges on the inner porcelain, as well as the transformer's effect on bushing behavior. The diagnostic methods used to evaluate oil and inner porcelain contamination are presented along with results of various case studies.

INTRODUCTION

Today a large population of aging high-voltage transformer bushings exists. The issue of determining their life span is a vital one. At the 1996 CIGRE SC12 discussion meeting [1], an opinion that the failure rate of bushings is insignificant when related to the overall population of bushings was expressed. However, transformer failure analysis shows that in many cases, the bushings were initially the faulty component. High-voltage bushing failure is often followed by catastrophic event such as an explosion, tank rupture, fire, etc. [2]. As determined through analysis of the replies to the Doble Annual Technical Questionnaires, an average of 10% of transformer failures are caused by bushings. This number can be even higher for large power transformers. References [13-15] pertaining to the failure rate of bushings shows that irrespective of their geographical location or differences in design, high-voltage bushings remain one of the weakest components and may have been the cause of up to 30% of all of the large transformer failures.

Because of preventive maintenance, the number of defective bushings removed from service annually is ten times the number of failed bushings. As gained from replies to Doble Technical Questionnaires over the period of 1992 -1996, over 1200 transformer bushings have been replaced based on the unacceptable test results. Many failures were prevented due to the timely removal of bushings when unreliable design was recognized [3-9].

The objective of this paper is to summarize typical defects and failure-modes of high-voltage bushings and to discuss methods for improvement of on- and off-line diagnostic techniques.

BUSHING DESIGN FEATURES

The most effective and economical monitoring and maintenance system should focus on the detection of defects which can occur with certain bushing designs while under certain in-service conditions. Typical bushing design features are summarized in Table I. This paper will concentrate on problems associated with oil-impregnated paper bushings which comprise the basic population of EHV apparatus. Experience with resin-bonded paper bushings [8, 17] has shown that the fault development process and the diagnostic parameters are similar to those in oil-impregnated bushings, but the level of our experience with aged EHV resin-impregnated bushings is not sufficient to make comparative conclusions about long-term reliability.

The condenser core is made up of a compressed bulk of oil-paper insulation that is very sensitive to localized defects. One of the goals of a bushing designer is to obtain the optimum dimensions of the core and porcelain housing while at the same time preventing incipient ionization under the operational voltage. The physical nature of incipient ionization in defect-free insulation is a puncture of interlayer oil...
[18], which can be observed in ac field strength of 12-15 kV/mm. The corresponding discharge is in the range of 0.1 to 10 pC and the frequency is in the range of 1 to 10 MHz.

**TABLE I**

**Bushing Design Features**

<table>
<thead>
<tr>
<th>Features</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser core</td>
<td>Oil impregnated</td>
</tr>
<tr>
<td></td>
<td>Resin-bonded</td>
</tr>
<tr>
<td></td>
<td>Resin-impregnated</td>
</tr>
<tr>
<td>Condenser graded layers</td>
<td>Conductive foil (aluminum)</td>
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<tr>
<td></td>
<td>Printed semiconductive ink</td>
</tr>
<tr>
<td></td>
<td>Semiconductive paper</td>
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<tr>
<td>Conductor lead</td>
<td>Draw lead</td>
</tr>
<tr>
<td></td>
<td>Draw rod</td>
</tr>
<tr>
<td></td>
<td>Center conductive tube</td>
</tr>
<tr>
<td>Cooling of central conductor</td>
<td>Oil channel (convection)</td>
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<tr>
<td></td>
<td>Heat conduction through core</td>
</tr>
<tr>
<td>Taps</td>
<td>Potential tap</td>
</tr>
<tr>
<td></td>
<td>Test tap</td>
</tr>
<tr>
<td>Oil protection</td>
<td>Open breathing</td>
</tr>
<tr>
<td></td>
<td>Nitrogen (air) sealed (alternating pressure)</td>
</tr>
<tr>
<td></td>
<td>Membrane sealed</td>
</tr>
<tr>
<td></td>
<td>Permanent oil extra pressure</td>
</tr>
<tr>
<td>Type of installation</td>
<td>Within separated pocket</td>
</tr>
<tr>
<td>(Position of lower porcelain)</td>
<td>Within top adapter</td>
</tr>
<tr>
<td></td>
<td>Between winding and tank wall</td>
</tr>
<tr>
<td></td>
<td>Between winding (core)</td>
</tr>
</tbody>
</table>

Another task of the bushing designer is to avoid the development of critical ionization when gas generation in the oil due to partial discharge (PD) exceeds the rate of gas absorption. The quality and gas tendency of the oil and PD incipient voltage is of a great importance. Experience has shown that excessive gas generation can occur within one minute of the ac test on the bushing, if the quality of oil does not meet the electrical field stress needs.

A very important design factor which should also be considered is the transformer's impact on the bushing's performance [2, 9]. The following transformer effects on the bushing's thermal performance should be noted:

- Hot transformer oil as one of the main sources of bushing heating.
- Heat radiated from the tank top cover as a source of elevating the temperature of the cooling medium (air surrounding bushing).
- Impairment of oil convection within the bushing when transformer load is essentially lower than the rated current of the bushing.

The following transformer effects on the bushing's dielectric performance should be noted:

- Higher electrical stress within the bushing, specifically, in the oil between the bushing core and lower porcelain due to the close proximity of conductive layers to the grounded components and/or HV winding of the transformer.
- Unlike the core insulation, which can be properly tested while the bushing is out of the unit, insulation space between the bushing core and lower porcelain can be reliably tested only under conditions that replicate those in a transformer [2, 10].
ZTZ-Service Company has the opportunity to observe periodically a large population of 110-750 kV bushings with the following features:

- oil-impregnated paper core insulation
- foil layers for transformer bushings and semiconducting paper layers for shunt reactor bushings
- draw lead conductors with top connections
- oil cooling channels between the central tube and the core for a bushing above 1600 A; 110, 150, and 220 kV transformer bushings and 500 and 750 kV reactor bushings are equipped with test taps; 330, 500, and 750 kV transformer bushings are equipped with potential taps;
- free-breathing design for bushings manufactured before 1972; permanent oil extra pressure protection with sealed compensators manufactured after 1972;
- all types of bushing installation as presented in Table I

**TYPICAL DEFECTS AND FAILURE-MODES OF HIGH-VOLTAGE TRANSFORMER BUSHINGS**

A bushing failure model is presented in Figure 1. The failure analysis which was based on information gathered from various Doble Conference papers as well as replies to the Technical Questionnaires over the period of 1989-1996, created the following observations:

- Most failures that occur are due to aging. Approximately 80% of failures take place after 10-12 years in service. Over 30% of failures occur after 20-25 years in service.
- Bushing design deficiencies are typically involved.
- Core failures generally occur in unsealed designs (or when the seal is broken) due to ingress of water, aging, excessive dielectric losses, and migration of printed ink (in specific designs).
- Typical failure mode for relatively new bushings is de-impregnation when the bushing has been stored without sufficient oil pressure.
- In 220-750 kV bushings there were fewer problems with the core than those related to discharges in oil, overheating, and external flashovers.
- In most cases, internal flashover in the lower porcelain is caused by oil aging.
- Overheating due to loose contact of conducting components is related to aging.
- The objectives of a monitoring and diagnostic system should be as follows:
  - identification of the local fault in the core
  - detection and identification of oil and internal surface contamination
  - detection of overheating in the conductor contacts
  - prevention of bushing explosions

**Bushing Core**

*Defect-free condition of oil-paper core*

A defect free oil-impregnated paper bushing core should exhibit the following characteristics:

- Water content of paper is \(< 0.3-0.5\%\).
- Paper should be well impregnated.
- Dry clean oil with low dielectric losses, high level of aging resistance, high level of PD incipient voltage, with tendency to absorb gasses in presence of PD.
- A near constant value of capacitance \(C_1\) (no significant change with temperature).
- Dissipation factor \(\tan \delta_{C1}\), depending on the paper density and \(\tan \delta\) of oil, should be 0.3-0.5\% at temperatures \(\leq 90^\circ\text{C}\). For example, if the density is 0.8 g/cm\(^3\) and the tan \(\delta_o = 0.3\% @ 90^\circ\text{C}\), than the tan \(\delta_{C1} = 0.4\% @ 90^\circ\text{C}\).
- "U-shape" relationship between tan \(\delta_{C1}\) and temperature.
- No incipient stable PD (> 1pC) @ maximum rated voltage \(U_{\text{m}} / \sqrt{3}\)
Typical Defects and Failure Modes of High-Voltage Bushings

FIGURE 1

- No incipient stable PD (> 10 pC) @ \( \frac{2U_{cm}}{\sqrt{3}} \).
- No signs of critical ionization during one minute ac test, where critical ionization is a condition when the amount of generated gas exceeds the amount of absorbed gas.
- Minor tip-up \( \tan \delta_{ci} \) with voltage \( (0.3U_m...0.85\ U_m) \).
- \( \tan \delta_{ci} = \tan \delta_{ci} \).

New bushings typically meet the above specifications [21], however, some non-uniformities or differences in materials can also be considered acceptable. For example, IEC-137 (1984) recognizes \( \tan \delta_{ci} \leq 0.7\% \), tip-up \( \leq 0.3\% \) in the voltage range of \( 0.3\ U_m...0.85\ U_m \), and the PD level of \( \leq 10\ pC \) @ \( 0.85\ U_m \).

**Overall moisture contamination**

Our experience has shown that the effects of water on dielectric characteristics of oil-impregnated bushings can be summarized as follows (image of the defect) [11, 20]:

- Increase of \( \tan \delta_{ci} \) with an increase in temperature. For example, water content of over 2% was observed when \( \tan \delta_{ci} \) increased from 0.3% @ 20°C to 0.6% @ 40°C, and to 1.0% @ 70°C.
- Reduction of polarization index: \( 1 \leq R_{ci}/R_{c} \leq 1.2 \).
- At rated voltage the PD level is \( 10^3 \) - \( 10^4 \) pC with a water content above 4.0%.
- Increase of the water content in the oil with an increase in temperature.

**Localized moisture contamination**
In cases where a bushing experiences water ingress, the bushing condition is such that free water collects at its bottom. This will result in severe moistening of the end of the core. Actually only 10-15% of the bulk of the core may have excessive water content. In this case the equivalent tan δ \(e\) can be expressed as follows:

\[
\tan \delta_e = (0.1 - 0.15) \tan \delta_i + \tan \delta (0.9 - 0.85)
\]

where \((d)\) designates the defective area and \((n)\) represents the defect-free area.

For example, if the water content in the lower part of the core is 5%, the tan δ \(e\) will increase to 4.5% at 30°C and to 20% at 60-70°C [27]. Correspondingly, equation (1) will produce the following results: for tan δ \(e\) = 0.5%, tan δ \(e\) will change to 0.8...0.95% @ 30°C and to 2.45...3.4% @ 60-70°C [27]. Increasing water content in oil above 30-40 ppm by heating the lower part of the bushing to 60-70°C, may be used as a complementary diagnostic parameter.

Localized defect

Irrespective of the origin of the defects shown in Figure 1, the physical nature of these faults would fall into one of two categories:

- Electrical destructive ionization in the area of overstress.
- Thermal dielectric overheating.

Defective areas with excessive conductance develops between two or more layers. The defect can be characterized by two parameters:

- Dissipation factor of defective area - tan δ \(e\) = t.
- Relative portion of defective section - \(\alpha = C_e / C_o\)

where \(C_e\) and \(C_o\) are capacitances of the defect-free and the defective portions of the core.

Furthermore, the process of the defect development can be described as an increase in conductivity and tan δ \(w\), followed by burning of the paper, and finally development of a short-circuit between two or more layers. This will result in a change of the conductance measured between the central tube and the potential (or test) tap. Our experience has shown that the presence of the short-circuited layers in the bushing core will result in the following:

- Change in the dissipation factor of the core tan \(\sqrt{\delta I}\)
- Change in the measured dielectric losses \(P_c\)
- Change in the C, capacitance due to short-circuit between layers and to some extent due to an increase in the permittivity of the defected areas.
- Change in the leakage current at the bushing tap, I, mainly due to change in C.
- Change in sum current which is the sum of the leakage currents from three bushings.

We refer to the above description as the image of the defect. The diagnostic parameters that define the image of the local defect in the core are summarized in Table III.

All of these parameters will change with the development of a localized defect, which will result in the short-circuit between layers. However, the sensitivity to each defect will be different. The behavior of diagnostic parameters as a function of \(\tau\) is presented in Figure 2.
Comparative Sensitivity of Diagnostic Parameters to Local Defect in the Core

FIGURE 2

As is apparent from the plots, the most sensitive parameters during the early stages of defect development are:

1. Sum current and (or) modulus of relative change of bushing leakage current.
2. Relative change in losses.
3. Change in tan δ₁.

When a fault has developed, the more sensitive parameters are:

1. Sum current or modulus of relative change of leakage current.
2. Relative change in leakage current.
3. Relative change in capacitance.

TABLE III
Diagnostic Parameters for Identification of Local Defect in the Core
Possible failure mechanism

Discharges along the inner bottom porcelain are the result of typical aging of the bushing. The failure process is initiated within the oil channel between the core and the lower porcelain. Electric field distribution in the oil channel, along the surface of the lower portion of the core and the inner porcelain is established by both the design of the bushing insulation and by the disposition of the bushing's end in relation to the grounded parts and the winding. The failure process which was partially presented in references [9, 10, 11, 12, 22, 23] may be summarized as follows:

- aging of oil
- formation of oil decay, particularly, colloids containing atoms of metals
- coagulation of non-uniformities and deposits of semiconductive sediment on the surfaces
- reduction of the oil dielectric strength
- changes in the voltage distribution along the porcelain
- appearance of discharge in the oil, especially during switching transients; gas generation
- surface discharges and flashover

Factors influencing failure development

An electrical field has the following influence on failure development in the oil:

- Close proximity of the bushing's end to grounded components can increase field intensity by 20-25% and essentially distort the inner field distribution.
• In certain cases (certain shunt reactor designs) a large stressed volume of oil is set up, which is extremely sensitive to oil contamination.
• A spare margin of the bushing's dielectric integrity is determined by the dielectric strength of the oil channel between the core and porcelain. A reduction of the oil's dielectric strength can significantly reduce this margin and cause partial discharge activity.
• The electrical field impacts the chemical reactions in the oil, which contributes to the coagulation of colloids.

Heat generated by the transformer has the following influence on the failure development in the oil:

• Heat radiated from the transformer determines the air temperature surrounding the external portion of the bushing.
• Transformer oil is the main source of bushing heating. Two additional sources are dielectric losses in the core and resistive losses in the conductor. The latter will not significantly influence the temperature distribution when the current is less than 50% of the rated value.
• The main heat exchange is in the oil channel between the core and porcelain, specifically, near the bottom of the mounting tube close to the top oil level in the transformer. The maximum temperature of bushing oil can be equal to or exceed the top oil temperature of the transformer.

Summary of investigations

The results of the investigating several thousand 110-750 kV bushings including several hundred units under teardown, have shown the following:

• Increase in the oil dissipation factor of 5 up to 60% at 90°C.
• Reduction of the oil dielectric breakdown, especially in samples drawn from the bottom of the bushing.
• Presence of colloids containing atomic metals (copper, aluminum, zinc, etc.).
• Presence of combustible dissolved gasses typically created by PD in oil.
• Deposits of oil decay on the core and lower inner porcelain. Discoloration of the porcelain from a light yellow to a dark brown color. The sediments could be wiped away.
• Traces of discharge (trees) on the porcelain surface, at times with glaze damage.

Special tests performed on bushings that were removed from service due to an excessive value of the oil dissipation factor have shown that often they will pass the high-voltage routine tests performed on new bushings. For example, three 150-kV bushings with an oil tan d of 70-100%, and with the lower inner porcelain coated with deposits (as was revealed after the test), successfully withstood 375 kV ac for 1 minute.

Diagnostic characteristics

The following diagnostic characteristics can be used to identify two stages of failure mechanism development (image of the defect):

a) Stage I - deteriorated oil, porcelain contaminated with semiconducting sediment
• changes in dissipation factor and resistivity of the oil
• appearance of colloids (change in optical characteristics)
• increase in dissipation factor of C<sub>2</sub> insulation, especially with temperature
• reduction in dissipation factor of C<sub>1</sub> insulation with a rise in temperature
• change in sum current

b) Stage II - discharges on the inner porcelain
• combustible gases typically seen for PD in the oil
• dissipation factor is reduced to a negative value
Evaluation of oil deterioration using $C_2$ test

The insulation space between the grounded tapped layer and the ground sleeve is typically composed of a thin support paper layer wrapped around the tapped layer and the oil channel. An equivalent circuit can be presented as a series connection of the paper layer impedance and the oil impedance. Correspondingly, the equivalent dissipation factor $\tan \delta C_2$ tested by GST-Guard test circuit can be expressed as

$$\tan \delta C_2 = K_p \cdot \tan \delta_p + K_o \cdot \tan \delta_0 + \Sigma \tan \delta_{int}$$

where $\tan \delta_p$ and $\tan \delta_0$ are the dissipation factors of the oil and support paper, and

$$K_p + K_o = 1$$

$$K_p = \frac{C_p}{C_p + C_o} - \text{relative capacitance of the paper}$$

$$K_o = \frac{C_o}{C_p + C_o} - \text{relative capacitance of the oil}$$

$\Sigma \tan \delta_{int}$ - additional loss factor due to possible contamination of the tap insulator, upper porcelain and external interference. Typically $K_o = 0.1 - 0.2$, and the influence of interference can be removed. Therefore, the dissipation factor of $C_2$ insulation is influenced predominantly by $\tan \delta_0$ of the oil.

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The relationship between the oil deterioration and the dissipation factor of the $C_1$ insulation has been demonstrated. Six bushings rated 150 kV, 2000 A, equipped with test taps, were tested after 12-13 years of service to investigate changes in dielectric characteristics with temperature. The bushings exhibited various degrees of oil deterioration and different degrees of lower porcelain internal discoloration from light yellow to dark brown (evident after dismantling) due to deposits of oil decay. The bushing mounting flanges were isolated from ground to permit the UST measurements. The bushings were heated in steps up to 70-75°C using hot air. The $C_1$ and $C_2$ dielectric characteristics were tested at various temperatures.
Effect of Temperature on Dissipation Factors of Bushing Oil, C₂ and C₁ Insulations in 150 kV Bushings.

a) bushing with severely deteriorated oil, b) bushing with slightly deteriorated oil, c) correlation between dissipation factors of C₂ insulation and oil (for all six bushings)

FIGURE 3

Figure 3 shows the dissipation factor plots for C₁, C₂ insulation and the oil samples versus temperature for severely contaminated bushing (tanδ₀ above 15%, dark brown deposits on the inner porcelain), for a slightly contaminated bushing (tanδ₀ = 1.0%), and a correlation between C₂ insulation dissipation factor and oil for all six bushings. It was determined that tanδ₂ follows tanδ₀, so that the oil condition can be predicted using tanδ₂ value. However, it is difficult to recognize oil deterioration while at relatively low oil temperature, e.g., 20°C or less, because of the low values of tanδ₂.

Estimation of tan δ, using tan δ₂ measured at two temperatures

Use of the following method was suggested to estimate the condition of the oil (without sampling) using results of tests on the C₂ insulation [23]. Prior to deenergizing, the unit is heated by reducing the cooling to a top oil temperature of 60-70°C. The transformer is then deenergized and the tan δ₁C₂ is measured at temperature T₁. The temperature of transformer oil is then reduced by 20-30°C by turning the cooling system on. At this time the second value, tan δ₂C₂ is obtained at temperature T₂. If the paper insulation is dry (or slightly wet) component (K, tan δₚ) in equation (2) is small and is not influenced significantly by temperature. Therefore, using equation (2):

$$\Delta \tan \delta C₂ = \Delta \tan \delta₁C₂ = \tan \delta₂ - \tan \delta₁$$
Because $\Delta \tan \delta_C$ is proportional to the change in the oil $\tan \delta$ with temperature, it is utilized in the described method. The dissipation factor of oil $\tan \delta_1$ at $T_1$ can be determined as:

$$tan \delta_{10} - (1 + \alpha) \cdot K (\tan \delta_{1C2} - \tan \delta_{2C2}), \quad (4)$$

and $\tan \delta_2$ @ 70°C used as diagnostic parameter is calculated as:

$$\tan \delta_{070} = \tan \delta_{11} \cdot e^{0.04(70-11)}$$

where

$$\alpha = C_1C_4$$

$$K = 1[1 - e^{-\beta(t_1 \cdot t_2)}]$$

$$\beta = 0.04$$

The value of $\alpha$ is typically 0.1..0.2. Neglecting $\alpha$ will not significantly influence the oil condition assessment. However, the condition of the oil may appear approximately 20% better than it actually is. This technique has been in use for nearly eight years and our experience has confirmed the effectiveness of the approach. An investigation of about 400 bushings rated 150 kV showed that a temperature dependency of the bushing oil up to 70°C corresponds with a temperature dependency of the transformer oil, i.e., $\beta = 0.04$. In bushings that contain deteriorated oil, where the inner porcelain had a typical yellow coloration, the oil $\tan \delta @ 90°C$ often was lower at 70°C. This could be the result of colloids dissolving at higher temperatures.

Table IV presents some of the results for 110-500 kV bushings. There is a good correlation between the estimated data and the results of the direct measurements performed on oil samples. Power and Distribution Corporation Kievenergo identified over 30 bushings using this method and then replaced them. Further investigations revealed severe oil deterioration, discoloration of the inner porcelain, and traces of discharge along the inner porcelain (in seven bushings). The data presented in Table IV was calculated as follows:

For case #2:

$$K = 1/[1 - e^{-0.04(31-37)}] = 2.332$$

$$\tan \delta_{e31} = (1 + 0.11)2.332(5.3 - 2.5) = 7.25\%$$

$$\tan \delta_{o70} = \tan \delta_{e31} e^{0.04(70-31)} = 15.5\%$$

### TABLE IV

<table>
<thead>
<tr>
<th>No.</th>
<th>Bushing Rating</th>
<th>Bushing Oil Temperature*</th>
<th>$\tan \delta_{C2}$</th>
<th>$\tan \delta_0$ of Oil @ 70°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T_1$</td>
<td>$T_2$</td>
<td>$T_1$</td>
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<td>1</td>
<td>110 kV, 2000 A</td>
<td>51</td>
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<td>51</td>
<td>37</td>
<td>5.3</td>
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<td></td>
<td>DC Resistance of Tap Insulator, $R_2$ [MΩ]</td>
<td>tan $\delta_{c2}$ [%]</td>
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<td></td>
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<td>6</td>
<td>$\alpha = 0.1$</td>
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<td>6.9</td>
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<td>7</td>
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<td>6.2</td>
<td>3.2</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>32</td>
<td>0.92</td>
<td>0.51</td>
</tr>
</tbody>
</table>

*Bushing temperature was determined as average between air and top oil temperatures.

**Effect of tap insulation condition on $C_2$ test**

Tap insulator surface contamination causes a reduction in the $C_2$ resistance and will result in additional losses and tip-up of $\tan \delta_{c2}$. The results of an experiment using a 150-kV bushing and artificial moistening of the insulator is presented in Table V.

**TABLE V**

**Effect of Tap Insulator DC Resistance on $C_2$ Test**

To avoid the negative effect of the tap insulator condition, dc insulation resistance should be measured prior to the $\tan \delta$. The minimum value of $R_{2\text{min}}$ can be expressed as:

$$R_{2\text{min}} \geq \frac{1}{\omega C_2 \Delta \tan \delta}$$

where $\omega = 2\pi f$ and $\Delta \tan \delta$ is a permissible error. Assuming $\Delta \tan \delta \leq 0.2\%$, $C_2 = 1000$ pF, and $f = 60$, $R_{2\text{min}}$ is determined as:

$$R_{2\text{min}} \geq \frac{1}{\omega \times 10^{-4} \times 1000 \times 0.2} \approx 1326 \text{ MΩ}$$

**Bushing Inner Porcelain**

Increased conductivity of the inner porcelain due to semiconducting deposits as well as the appearance of creeping discharges are characteristics of a defective bushing condition. The inner porcelain surface condition can affect the dielectric characteristics of the core because of capacitive coupling between condenser layers and porcelain. There is some uncertainty associated with the level of contamination and the value of contaminant conductivity. Therefore, the effects of porcelain surface contamination cannot be estimated. The $\tan \delta_{c1}$ can increase, decrease, and even become negative depending on the contamination pattern. However, service experience has shown that in most cases deposits on the inner porcelain reduce $\tan \delta_{c1}$.

An investigation of 500 bushings rated 150 kV at "Dneproenergo", one of the largest power companies in Ukraine, revealed that 40 bushings had $\tan \delta_{c1}$ at less than 0.3% [24]. Oil test results showed an increase
of tanδ of oil on the average up to 5.5% at 90°C and severe discoloration of the inner porcelain. In one of the bushings with negative tanδ, traces of PD on the porcelain were observed. The main findings of this investigation can be summarized as follows:

- Effect of semiconducting deposits on the reduction of tanδ, increases with the reduction of oil tanδ.
- Increase of bushing temperature leads to an increase of deposit conductivity and correspondingly to the reduction of tanδ.

Item two was confirmed in an experiment performed on two 110 kV bushings. These bushings were removed from service due to the detection of deteriorated oil. Although, the oil was changed, deposits of deterioration products remained. In both bushings a reduction of tanδ with temperature was observed. Figure 5 shows the change in tanδ with temperature. Measurements were performed at 10 kV (solid line) and 73 kV (dotted line).

Influence of the contaminated surface of the inner porcelain can be analyzed using simplified equivalent circuit shown in Figure 6. Capacitive coupling between the core and the porcelain is represented by C, and deposits on the porcelain by R. Resistance R is divided in two components $R_c(1 - \beta)$ and $R_{ep}$, where $0 < \beta < 1$. 

![Dissipation Factor of C1 Insulation Versus Top Oil Temperature in Aged 110-kV Bushings after Changing Deteriorated Oil](image.png)
Influence of Contaminated Surface of Inner Porcelain on $C_1$ Measurement. Equivalent Circuit

**FIGURE 6**

The relative change in the modulus of the sum current (monitored on-line as a sum of three leakage currents) due to deposits on the inner porcelain is equal to:

$$0 \leq l_0^* = \frac{\gamma}{\sqrt{1 + \tan^2 \delta_p}} < \gamma$$

(9)

where

$\gamma = \alpha \beta$

$\alpha = C/C_1$

$\tan \delta_p = \omega R_p C_1[\beta / (1 - \beta)]$

Capacitance $C_1$ is of the order of 10 pC, so that $\alpha$ is of the order of 0.02 if $\beta = 0.5$, and $\gamma = 0.01\%$. Therefore, a change can be expected in the measured current due to deposits of contaminants on the order of several percent. The presence of discharges will contribute to the rise of current.

**CONCLUSIONS**

1. High-voltage bushings remain one of the "weakest" transformer components and cause near 1/3 of all large power transformer failures. Bushing failure modes depend on the type of bushing installation in the transformer, as well as the bushing design. Typical defects are: localized faults
in the condenser core; deterioration of oil followed by discharges along the inner porcelain, and overheating of conductor contacts.

2. Irrespective of nature, a localized defect in the core can be represented through dielectric parameters of the defective area. A diagnostic image of the defect can be defined as a set of dielectric parameters of the core measured off-line [dissipation (power) factor, change in dielectric losses, relative change in capacitance], as well as on-line (relative change in the modulus of the leakage current, modulus of the relative change in leakage current, and relative change of sum current). All diagnostic characteristics shall be analyzed in coordination. At early defect development stages, the most sensitive parameters are: sum current or modulus of the relative change in the leakage current, relative change in the losses, change in \( C_1 \) dissipation factor. When a fault has developed, the most sensitive parameters are: the sum current or modulus of a relative change in the leakage current, relative change in the leakage current, relative change in the capacitance.

3. Aging of the bushing oil and the evolution of an incipient fault depend on temperature conditions in the oil channel between the core and lower porcelain. The transformer's thermal and electrical effects on the bushing's condition should also be considered.

4. In bushings equipped with test taps, dissipation factor of bushing oil can be estimated through the difference in dissipation factors of \( C_2 \) insulation measured at two temperatures.

5. Contamination of the inner porcelain can be detected through reduction in \( \tan \delta \) with temperature.

6. On-line monitoring of the sum current, dissipation factor and leakage current can detect most of the probable defects in the high-voltage bushings.

REFERENCES


16. Pereira, A. Discussion of the Mark Jenson and Karl A. Bryan Paper "Chief Joseph Dam T1 A-Phase 230 kV GE Type U Bushing Failure Report", Minutes of the Sixtieth Annual International Conference of Doble Clients, 1993, Sec. 4-3.1 B.


BIOGRAPHIES

Victor V. Sokolov received his degree in electrical engineering from the Khar'kov Polytechnical Institute in Ukraine in 1962. In 1964 he completed a postgraduate program at the National Polytechnical Institute in Moscow with a major in Physics of Dielectric. His Ph.D., received in 1982 from Kiev Polytechnical Institute, is in the area of EHV transformer diagnostics. He started his professional career at the Transformer Research Center in Zaporozhye. Until 1990 Dr. Sokolov worked in the Installation and Maintenance Department at the Zaporozhtransformer Corporation in the area of reliability. Since 1990 he is a Technical Director of Scientific and Engineering Center "ZTZ-Service" Co. in Zaporozhye. Dr. Sokolov has published over 50 papers and is a member of CIGRE (SC #12, Transformers) and a Convenor of CIGRE Working Group #1218, Transformer Life Management.

Boris V. Vanin received his degree in electrical engineering from the Ural Polytechnical Institute in Sverdlovsk, Russia in 1949. His Ph.D., received in 1966 from Electric Power Scientific and Research Institute in Moscow, is in the area of Physics of Dielectric. In 1967 he completed postdoctoral program at the Moscow University with a major in Mathematics. Dr. Vanin is employed by Moscow Electric Power Institute in the Laboratory of Transformers. Since 1991 he is a consultant of ZTZ-Service Co. Dr. Vanin has published over 130 papers and is an author of several fundamental studies in the area of physical modeling of processes in cellulose insulation in loaded transformers, convective heat transfer in power transformers and high-voltage bushings, and electromagnetic characteristics of power transformers.

APPENDIX
The following discussion will describe case studies that ZTZ- Service Company has recently conducted.

Detection of Excessive Water Content

In 1996, ZTZ-Service Company investigated the conditions of seven autotransformers rated 200-250 MVA, 220/110 kV, installed in NEK (Bulgaria). These units have been in service for 22-23 years and the objective of the investigation was to assess the remaining life of these units. One of the tasks in the Life Assessment Program was to evaluate the condition of 110-kV bushings. These bushings were unsealed and suspected to contain excessive water. The power factor of the $C_1$ insulation at various temperatures was measured using the Doble M4000 insulation analyzer. The bushings were preliminarily heated with transformer oil and dielectric losses.

**Case 1: Bushing 110 kV, 1640 A, with test tap**

<table>
<thead>
<tr>
<th>$T_a$ [°C]</th>
<th>$T_{TO}$ [°C]</th>
<th>U [kV]</th>
<th>I [mA]</th>
<th>Watts</th>
<th>PF [%]</th>
<th>$C_1$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>29</td>
<td>10</td>
<td>1.1</td>
<td>0.268</td>
<td>2.43</td>
<td>350.1</td>
</tr>
<tr>
<td>26</td>
<td>45</td>
<td>10</td>
<td>1.109</td>
<td>0.465</td>
<td>4.20</td>
<td>352.8</td>
</tr>
<tr>
<td>26</td>
<td>65</td>
<td>10</td>
<td>3.7</td>
<td>1.495</td>
<td>8.24</td>
<td>359.4</td>
</tr>
</tbody>
</table>

An elevated value of power factor as well as a rise in power factor with temperature were symptoms of an elevated water content at approximately 5% [26]. An increase of $C_{hot}/C_{cool}$ ratio was also observed. Oil samples were taken from the bottom of the bushing and confirmed water contamination: dielectric breakdown (by IEC 156) - 17 kV, water content - 57 - 70 ppm.

**Case 2: Bushing 110 kV, 1600 A., liquid (oil) sealed, free-breathing oil protection, with test tap.**

<table>
<thead>
<tr>
<th>$T_a$ [°C]</th>
<th>$T_{TO}$ [°C]</th>
<th>Watts</th>
<th>PF [%]</th>
<th>$C_1$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>26</td>
<td>0.082</td>
<td>0.73</td>
<td>393.5</td>
</tr>
<tr>
<td>21</td>
<td>50</td>
<td>0.233</td>
<td>1.88</td>
<td>408.0</td>
</tr>
<tr>
<td>29</td>
<td>65</td>
<td>0.492</td>
<td>4.04</td>
<td>403.4</td>
</tr>
</tbody>
</table>

The estimated water content of the paper was 3-4%. However, the slope of power factor versus temperature is higher than what would be expected for insulation that is simply wet. Dielectric overheating was suggested as a cause. The DGA results appear to confirm this assumption (elevated CO, low ratio CO$_2$/CO, elevated C$_4$H$_{10}$ (butane -1) were typical of low temperature overheating):

| H, CH, C$_2$H$_2$, C$_3$H$_6$, C$_3$H$_8$, C$_4$H$_{10}$, CO, CO$_2$, $\sum C$, C$_4$H$_{10}$ |
|---|---|---|---|---|---|---|---|---|
| 28 | 38 | 20 | 37 | no | 754 | 1921 | 130 | 2381 |

The water content of the oil sample was 30 ppm.

Detection of Localized Defect in the Core

**Case 3. Bushing 420 kV, 1250 A, sealed with permanent oil excessive pressure, with test tap**

This bushing was installed in 250 MVA, 400/110 kV autotransformer, manufactured by MNF-TRO (AEG). Power factor measurements were performed in 1996 using the Doble M4000 insulation analyzer and revealed a fault in phase C.

<table>
<thead>
<tr>
<th>$T_a$ [°C]</th>
<th>$T_{TO}$ [°C]</th>
<th>U [kV]</th>
<th>PF [%]</th>
<th>$C_1$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Measurements performed at various voltages revealed power factor tip-up:

<table>
<thead>
<tr>
<th>U [kV]</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF [%]</td>
<td>1.330</td>
<td>1.526</td>
<td>1.668</td>
<td>1.79</td>
<td>1.91</td>
</tr>
</tbody>
</table>

Measurements performed in 1995 @ T_a = 24°C and T_TO = 37°C resulted in PF = 0.353% and C_1 = 337.67pF. An increase in power factor by 1.56%, relative independence of power factor from the temperature, and small increase in capacitance ΔC_1/C_1 = 0.7 were recognized as symptoms of ionization-mode fault in the area between 2-3 layers. DGA analysis performed by the ZTZ-Service laboratory confirmed the presence of high-energy discharges.

<table>
<thead>
<tr>
<th>H_2</th>
<th>CH_4</th>
<th>C_2H_6</th>
<th>C_2H_4</th>
<th>C_3H_8</th>
<th>CO</th>
<th>CO_2</th>
<th>C_3H_8</th>
<th>C_2H_4</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas lost</td>
<td>16</td>
<td>&lt;1</td>
<td>29</td>
<td>60</td>
<td>61</td>
<td>361</td>
<td>15</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

This bushing was replaced.

Case 4. Bushing 750 kV, equipped with on-line monitoring of the sum current (ΔI*). The monitoring system provides alerts at two levels of the sum current: "Alarm Signal" - 6.5% of leakage current; "Switching OFF" - 24% of the leakage current.

This bushing was installed in a shunt reactor. A change of the sum current by 54 mA (or 61% of the initial leakage current) over a period of 10 hours produced a high-priority alarm and tripped the reactor. An analysis of on-line diagnostic parameters and an assessment of the defected area suggested damage of more than 40% of the core insulation. 10-kV measurements showed a change in tanδ_c from 0.4 to 1.13% and a change in capacitance from 650 to 678 pC (by 4.3%). A localized defect with short-circuiting of some layers was suspected. DGA analysis confirmed the presence of a discharge in the oil-paper insulation.

<table>
<thead>
<tr>
<th>H_2</th>
<th>CH_4</th>
<th>C_2H_6</th>
<th>C_2H_4</th>
<th>C_3H_8</th>
<th>CO</th>
<th>CO_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>540</td>
<td>1400</td>
<td>230</td>
<td>80</td>
<td>1400</td>
<td>710</td>
</tr>
</tbody>
</table>

Once the core was dismantled traces of discharge between layers 41-90 (out of total 126) were revealed. Apparently, the 10-kV test voltage was not sufficient enough to maintain the ionization process throughout the damaged area.

Detection of Deteriorated Oil

Case 5. Bushing 200 kV, 2000 A, with test tap.

This bushing was installed in an autotransformer rated 200 MVA, 220/110 kV. The test results have shown symptoms of the deterioration process in the oil channel. Inner porcelain contamination was suspected due to a reduction of the C_1 power factor with an increase in temperature. The estimated values of oil power factor using results of C_1 measurements resulted in 2.05% @ 70°C and 4.5% @ 90°C.

<table>
<thead>
<tr>
<th>Test</th>
<th>T_a [°C]</th>
<th>T_TO [°C]</th>
<th>PF [%]</th>
<th>C_1 [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_1</td>
<td>21</td>
<td>27</td>
<td>0.44</td>
<td>561.6</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>46</td>
<td>0.39</td>
<td>562.6</td>
</tr>
</tbody>
</table>
The power factor results from the oil sample tested at ZTZ- Service laboratory were as follows:

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>PF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.25</td>
</tr>
<tr>
<td>50</td>
<td>1.37</td>
</tr>
<tr>
<td>70</td>
<td>2.5</td>
</tr>
<tr>
<td>90</td>
<td>5.15</td>
</tr>
</tbody>
</table>

Signs of colloids were detected in the oil sample.

**Detection of Contaminated Inner Porcelain**

**Case 6. Bushing 500 kV, 1600 A, with potential tap, equipped with on-line monitoring of sum current.**

This bushing was installed in an autotransformer rated 250 MVA and 500/110 kV. The fault developed four months following acceptable results shown by routine off-line tests. Ten days prior to failure the sum current began to rise. Over the next five days, $\Delta I^*$ increased from an initial level of 0.7% to 1%, then four days later to 1.5% and, finally, to 1.8% one day prior to failure. Three minutes prior to failure the sum current exceeded the alarm level of 6.5%. Evidence of oil decay and traces of surface discharges were revealed on the inner porcelain.

**Case 7. Bushing 750 kV, 1000 A, with potential tap, equipped with on-line monitoring system.**

This bushing was installed in an autotransformer rated 333 MVA and 750/330 kV. The objective of the test was to evaluate the dielectric characteristics under severe interference conditions using the line-frequency modulation technique of the Doble M4000 insulation analyzer.

<table>
<thead>
<tr>
<th>Test</th>
<th>$T_a$ [°C]</th>
<th>$T_{TO}$ [°C]</th>
<th>U [kV]</th>
<th>I [mA]</th>
<th>Watts</th>
<th>PF [%]</th>
<th>$C_1$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>17</td>
<td>41</td>
<td>10</td>
<td>1.669</td>
<td>0.04</td>
<td>0.24</td>
<td>531.4</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>60</td>
<td>10</td>
<td>1.674</td>
<td>0.245</td>
<td>-1.46</td>
<td>532.7</td>
</tr>
<tr>
<td>$C_2$</td>
<td>17</td>
<td>41</td>
<td>10</td>
<td>159.6</td>
<td>6.748</td>
<td>0.42</td>
<td>508.20</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>60</td>
<td>10</td>
<td>160.1</td>
<td>8.054</td>
<td>0.5</td>
<td>509.70</td>
</tr>
</tbody>
</table>

The detection of negative power factor with an increase in the bushing temperature was recognized as a symptom of porcelain inner surface contamination. Because insulation failures had not occurred with this type of bushing, it was decided to leave this bushing in operation under observation of the on-line monitoring system until the summer of 1997.