

EVALUATION AND IDENTIFICATION OF TYPICAL DEFECTS AND FAILURE-MODES OF 110-750 KV BUSHINGS

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ABSTRACT

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This paper discusses the typical defects and failure-modes of HV transformer bushings on the base of service experience of a huge bushing population and failures studies. Failure developing considerations, determination of defective condition and images of defects are presented. Specific failure-mode caused by deterioration and appearance of discharges across the inner part of the transformer-end porcelain is discussed as well as effect of transformer itself on bushing behavior. Some diagnostic technique, particularly, methods of evaluation of the oil condition and inner porcelain contamination are presented with complementary typical examples and cases history.

INTRODUCTION

There is a huge aged population of HV transformer bushings and problem of their actual Life Span is a vital one.

At 1996 CIGRE SC-12 discussion meeting ¹ an opinion was expressed that failure rate of bushing is small and nearly negligible relative to general population of bushings. However, transformer failure analysis shows that in many cases bushings were involved as initially faulty component. Failure of HV bushing is often followed with catastrophic consequences as explosion, tank rupture, fire, etc. ²

As follows from analysis of Doble Clients Replies to annual Technical Questionnaires in average about of 10% of transformer failures cause by the bushings damage. This percent is essentially more for Large Transformers.

Some information about relative failure rate of bushings collected from ^{13,14,15} shows that irrespective of geography of transformer installation and difference in design, HV bushings remain as one of the weakest components and may cause from the fifth to the third part of general large transformer failures.

Thanks to developed preventive maintenance number of defective bushings which annually removes from service more than in ten times as many as failed number. As follows from Doble Clients Replies on Technical Questionnaires in 1992-1996 during 5 years over 1200 transformer bushings have been replaced basically due to negative test results.

Apparently many failures were prevented due to scheduled removing the bushings from service which design was recognized as unreliable. ^{3... 9}

One can suppose that condition of replaced bushings was different and advising more reliable methods of identification of defects could significantly reduce maintenance costs.

On the other hand, in some cases bushings have been exploded without any significant sign of faults prior to failure. The typical unexpected failure-mode involves flashover along the internal surface of the lower porcelain^{11, 12}.

In June 1996 an expert of ZTZ-Service Co. took part in investigation of GSU 360 MVA/161 kV failure at Dairy Land Power Cooperation, which caused by explosion of the 160 kV GE type "U" bushing, catalogue # 11B424, manufactured in 1977.

The main cause of the fault was deterioration of oil, deposit deterioration products on the inner surface of the lower porcelain what resulted in formation partial discharge along the inner surface of low porcelain.

There was no chance to recognize the incipient fault in oil by means of used traditional methods.

This type of bushing fault has been introduced in several papers^{2, 9, 10, 12}, however, mechanism of failure initiation and developing is still not clearly understood.

The goal of this paper is an attempt to summarize the typical defects and failure-modes of HV bushings and to discuss some methods to improve Off-Line and On-Line diagnostic techniques.

BUSHING DESIGN FEATURES

The most effective and the least expensive Monitoring and Maintenance system shall be centered on detection of defects which really may occur in the certain design under certain operation condition.

Some typical bushings design features are summarized in Table I.

This paper is dedicated to the internal latent-mode problems in oil-impregnated paper bushings which introduce the basic population of EHV apparatus. However, well-known experience with resin-bonded paper bushings^{8, 17} has shown that fault-developing process and diagnostic parameters are similar to those in oil-impregnated type.

Experience with aged EHV resin-impregnated type is, on our opinion, not significant to make comparative conclusion about long-term reliability.

TABLE I

BUSHING DESIGN FEATURES

FEATURES	TYPICAL PERFORMANCE
Type of condenser core	Oil impregnated Resin bonded Resin impregnated
Type of condenser graded layers	Conductive foil (aluminum) Printed semiconductive ink Semiconductive paper
Type of conductor lead	Draw lead Draw rod Center conductive tube
Cooling of central conductor	Oil channel (convection) Heat conduction through core

Taps	Potential tap Test tap
Oil protection	Open breathing Nitrogen (air) sealed (alternating pressure) Membrane sealed Permanent oil extrapressure
Type of installation (Disposition of lower porcelain)	<ul style="list-style-type: none"> • Within separated pocket • Within top adapter • Within the winding and the tank wall • Between winding (core)

The condenser core is a well-stressed bulk of oil-paper insulation which is very sensitive to any local defect.

The goal of designer is to obtain the optimal dimensions of the core and porcelain housing and at a time to prevent incipient ionization under action of operational voltage. A physical nature of incipient ionization in defect-free insulation is puncture of interlayer oil¹⁸, which can be observed in AC field strength of 12-15 kV/mm. This strength of discharge is in the range of 0.1...10 pC and frequency range of 1...10 MHz.

Another task is to avoid appearance of critical ionization, when gas generation in oil due to PD is exceed rate of gas absorption.

The quality of oil and particularly PD incipient voltage and gas tendency of the oil under action of PD is of a great importance.

Experience has shown that an excessive gas generation can appear while 1 min AC test of bushing if quality of oil does not meet the electrical field stress.

The next very important factor which shall be taken into account in bushing design is impact of transformer (reactor) itself of bushing serviceability^{2, 9}.

One can underline the following effects:

- Effect on thermal behavior of the bushing
- Hot transformer oil is one of the main source of the bushing heating
- Heat radiated from the tank top cover is a source of elevating temperature of cooling medium (air around of bushing)
- Impairment of oil convection within the bushing, when transformer load is essentially lower than the rated current of the bushing
- Effect on dielectric behavior of the bushing

Strengthening electrical field within the bushing, specifically, in the oil between the core and lower porcelain due to approach of conductive layers to the grounded components and (or) HV winding of the transformer (in accordance with way of bushing installation). In the contrast with core insulation which can be properly tested in the bushing directly, insulation space between the core and lower porcelain can be reliable tested only on the conditions replicated or simulated installation of the bushing in the transformers^{2, 10}.

ZTZ-Service has opportunity to observe periodically a huge of 110-750 kV bushings (over 200, 900 bushing-year) having the following features (Table I):

- oil-impregnated paper type;
- foil layers performance for transformer bushing, semiconductive paper layer for shunt reactor bushing;
- mainly draw lead conductor with top connection;
- oil cooling channel between central tube and a core for bushing above 1600 A;
- 110, 150 220 transformer bushing and 500, 750 kV reactors bushing equipped with Test Tap 330, 500, 750 transformer bushing equipped with Potential Tap;
- open-breathing design for bushings which were manufactured before 1970-1972, permanent oil extra pressure protection with sealed compensators after 1972;
- all of 4 (see Table I) types of bushing installation.

TYPICAL DEFECTS AND FAILURE-MODES OF HV TRANSFORMER BUSHINGS

The Failure Model of bushings as collection of typical defects in functionally essential bushings parts and possible developing the faults into probable failure-mode is presented in Table II.

Qualitative assessment of faults and failure modes of priority which was performed on the base of failure analysis including information from Doble Conference papers and Replies on Technical Questionnaires in the period 1989-1996 brings to the following conclusion:

- Aged mode failure occurs predominantly. About 80% of failures take place after 10-12 years of service and over 30% after 20-25 years.
- Mainly deficiencies of bushing design are involved.
- Core failures happen mainly with unsealed design (or in case of breaking sealing) due to ingress of water, aging, excessive dielectric losses and also due to migration of printed ink (in specific design)
- Typical failure-mode of comparatively new bushing is deimpregnation while storing without excessive oil pressure
- Relative rate of core damage in 220-750 kV is significantly lesser in comparison with discharges in oil, overheating, external overflashing
- In the most cases internal overflashing within lower porcelain is involved due to predominantly oil aging
- Overheating due to looseness of conductive contacts is observed as a typical aging disease
- The task of priority for Monitoring and Diagnostic system shall be:
 - identification of the local fault in the core and prevention to its developing;
 - detection and identification of oil and internal surface contamination;
 - detection of conductor contacts overheating;
 - prevention of bushing explosion

DEFECT-FREE CONDITION OF OIL-PAPER CORE

- Water content in the paper is 0.3-0.5% or less

- Well impregnated oil- paper bulk
- Dry clean oil with low dielectric losses, high level of aging resistance, high level of PD incipient voltage, with tendency to absorb gasses under action of PD
- Practically, constant value of capacitance C_1 , no change C_1 with temperature
- Dissipation factor $\tan \delta C_1$ depending on the density of the paper and $\tan \delta$ of oil shall be 0.3-0.5% up to 90 °C. F.i., if density is 0.8 g/cm³ and $\tan \delta_0 = 0.3\%$ at 90 °C, $\tan \delta C_1 = 0.4\%$ at 90 °C
- “U-shape” relationship of $\tan \delta C_1$ with temperature
- No incipient instable PD ($> 1\text{pC}$) at maximal rated voltage $U_m/\sqrt{3}$
- No incipient instable PD ($> 10\text{pC}$) at voltage U_m or $2U_m/\sqrt{3}$
- No sign of critical ionization at AC 1 min. test $1.5 U_m$
- Minor tip-up $\tan \delta C_1$ with voltage ($0.3 U_m \dots 0.85 U_m$)
- $\tan \delta C_1 = \tan \delta C_2$ (potential tap)

Usually new bushings meet above mentioned characteristics, e.g. ²¹.

However, some non-uniformities or difference in materials are acceptable by specification IEC-137 (1984) specifies e.g. $\tan \delta_{C1} \leq 0.7\%$, tip up of $\tan \delta_{C1}$ with voltage in the range of $0.3 U_m \dots 0.85 U_m \leq 0.3\%$, PD level $\leq 10\text{pC}$ at $0.85 U_m$.

TABLE II
TYPICAL DEFECTS AND FAILURE MODES OF HV BUSHINGS

COMPONENT	DEFECT	FAILURE MODE
CONDENSER CORE	<p>LOCAL NATURE</p> <p>Residual Moisture Poor Impregnation Wrinkles in Paper Delaminated Paper</p> <p>Primary</p>	<p>Ionization Gassing Thermal Run Away</p>
	<p>Overstressing Short-circuit layer</p> <p>Ingress of Moisture</p> <p>Aging</p> <p>Ingress of Air Graphite Ink Migration Dielectric Overheating X-wax Deposit</p>	<p>Puncture Explosion</p>
	<p>BULK NATURE</p> <p>Aging of Oil-Paper Body Thermal Unstable Oil Gas Unstable Oil Oversaturation</p>	<p>Flashover Explosions</p>

CORE SURFACE	Contamination	PD
OIL	Moisture Contamination	Surface Discharge
	Aging	Gassing
INTERNAL PORCELAIN SURFACE	Deposited Impurities	
	Dip Lying Impurities	
TAPS	Ungroundings	PD
	Shorted Electrodes	
CONDUCTOR	OVERHEATINGS	Overheating
	• Top contact	Gassing
	• Foot contact	Sparkling
	• Draw rod	
	Circulating Current in the Head	
EXTERNAL PORCELAIN	Cracks	Flashover
	Contamination	
	Surface Discharge	

DEFECTIVE CONDITION DUE TO EXCESSIVE WATER CONTENT IN THE CORE

Excessive Overall Moisture

Effect of water on dielectric characteristics of oil-impregnated bushings was studied on the models of bushings²⁰. There were found the following characteristics:

- Exponential rise of $\tan \delta$ C_1 with temperature with water content above 1% .
- Significant rise of $\tan \delta$ with water content above 2.0-2.5%¹¹
- Reducing DC resistance and polarization factor R_{60} / R_{15}

Image of Defect

- Increasing $\tan \delta$ C_1 in accordance with characteristics of oil-impregnated cellulose
- Rising $\tan \delta$ C_1 with temperature. E.g., one can expect water content above 2% if $\tan \delta$ C_1 increases from 0.3 up to 0.6% at 20-40 °C and from 0.3 up to 0.9-1.0% at 60-70 °C
- Reducing polarization index $1 \leq R_{60} / R_{15} \leq 1.25$
- Appearance of PD at rated voltage up to $10^3 - 10^4$ pC with water content above 4,0%
- Increasing water content in oil with temperature

Local Contamination of the Core with Water

The typical condition of the bushing in case of ingressing water is collection some free water at the bottom and severe moistening the end of the core. Actually only 10-15% of the bulk may have excessive water content.

In this case equivalent Loss Factor can be expressed:

$$\tan \delta_1 \cong (0.1 - 0.15) \tan \delta_d + \tan \delta_n (0.9 - 0.85)$$

If water content at the end is e.g. 5%, $\tan \delta_d$ will increase up to 4.5% at 30 °C and up to 20% at 60-70 °C (top oil temperature). Correspondingly, for $\tan \delta_n = 0.5\%$ $\tan \delta_1$ will change up to 0.9...1.1% at 30 °C and up to 2.45...3.4% at 60-70 °C.

Increasing water content in oil above 30-40 ppm after heating the lower part of the bushing up to 60-70 °C may be used as a complementary diagnostic parameter.

LOCAL DEFECT WITHIN THE CORE

Irrespective of origin of defects which are shown in Table II two types of physical developing faults can be expected:

- Electric-destructive ionization in the place of overstressing
- Thermal-dielectric overheating

In any case, a defective area with excessive conductance is appearing between two or more core layers.

Defect can be characterized with two parameters:

- dissipation factor of defective area - $\tan \delta_d = \tau$
- relative portion of defective section - $\alpha = C_n / C_d$,
where C_n and C_d are capacitances of defect-free (C_n) and defective (C_d) portions of the core.

Further process of developing defect can be introduced as increasing conductivity and $\tan \delta_d$ then burning paper through and occurrence of short-circuit between two of several layers.

Correspondingly, change in dielectric parameters of defective area causes dielectric response of condenser core and change in partial conductance measured between the central tube and potential (or test) tap.

The image of local defect can be determined with the following characteristics:

- change in dissipation factor of the core $\tan \delta_1$
- change in measured dielectric losses P_{w1}
- change in C_1 capacitance due to short-circuit between layers and to some extent due to some increasing permittivity of defected area
- change in the leakage current at the bushing, I_0 mainly due to change in C_1
- change in imbalance current which introduces preliminary balanced geometrical sum of three phase bushings system due to increasing $\tan \delta_1$ and further increasing C_1

DIAGNOSTIC PARAMETERS FOR IDENTIFICATION OF LOCAL DEFECT IN THE CORE

- DISSIPATION FACTOR:

$$\tan \delta_1 = \tan \delta_n + \frac{\alpha \tau}{(1 + \alpha) + \tau^2} < \frac{\alpha}{2}$$

- RELATIVE CHANGE IN DIELECTRIC LOSSES:

$$P_w^* = \frac{P_w}{U^2 \omega C_0} = \frac{(1 + \alpha) \cdot \alpha \tau}{(1 + \alpha)^2 + \tau^2} \leq \frac{\alpha}{2}$$

This characteristic means also change in Power Factor on condition that capacitance of core is unchanged.

- RELATIVE CHANGE IN CAPACITANCE

$$\frac{\Delta C}{C_0} = \frac{C_1 - C_0}{C_0} = \frac{\alpha \tau^2}{(1 + \alpha)^2 + \tau^2} \leq \alpha$$

- RELATIVE CHANGE IN THE MODULUS OF LEAKAGE CURRENT

$$\frac{\Delta I}{I_0} = \frac{I - I_0}{I_0} = \frac{\alpha(\varepsilon + \alpha)\tau^2}{(1 + \alpha)^2 + \tau^2 + (1 + \alpha)\sqrt{\alpha^2 \tau^2 + (1 + \alpha + \tau^2)^2}} \leq \alpha$$

- MODULUS OF THE RELATIVE CHANGE IN LEAKAGE CURRENT

$$\left| \frac{\Delta \dot{I}}{\dot{I}_0} \right| = \left| \frac{\dot{I} - \dot{I}_0}{\dot{I}_0} \right| = \frac{\alpha \tau}{\sqrt{(1 + \alpha)^2 + \tau^2}} \leq \alpha$$

- RELATIVE CHANGE IN MODULUS OF IMBALANCE CURRENT OF THREE PHASE BUSHINGS

$$\Delta I^* = \frac{\alpha \tau}{\sqrt{(1 + \alpha)^2 + \tau^2}} \leq \alpha$$

All of the 6 parameters introduce diagnostic characteristic of the defective core with locally concentrated defect. All of them shall change with defect developing which follows with short-circuit between layers. However, sensitivity of those parameters to certain defect is different.

ANALYSIS OF COMPARATIVE SENSITIVITIES OF DIAGNOSTIC PARAMETERS

Dissipation Factor $\Delta \tan \delta_1$ as well as relative change in dielectric losses vary with rising τ non monotonously. They reach some maximal meanings equal to:

$$\Delta \tan \delta_{1\max} = \frac{\alpha}{2\sqrt{1+\alpha}} < \frac{1}{2} \quad \text{by} \quad \tau = \sqrt{1+\alpha}$$

$$P_{w\max}^1 = \frac{\alpha}{2} \quad \text{by} \quad \tau = 1 + \alpha$$

After reaching the maximal values they slow down to the initial meanings $\Delta \tan \delta_1 = 0$, $P_w^1 = 0$.

Relative change in capacitance as well as relative change in leakage current increase monotonously up to the maximal value equal to α , though $\Delta C / C_0$ is behind a little.

Both of these characteristics are essentially behind $\Delta \tan \delta_1$ and P_w^1 at early stage of defect developing but significantly lead after $\Delta \tan \delta_1$ and P_w^1 will reach their maximal values.

Modulus of relative change of leakage current and relative change of imbalance current are quantitatively equal. They of both carry information about rise as in power factor as well as in capacitance and increase monotonously up to value equal to α .

Comparative data about diagnostic parameters was collected in Table III (Appendix I) and shown in Figure 1, where one can see plots diagnostic characteristics versus to τ .

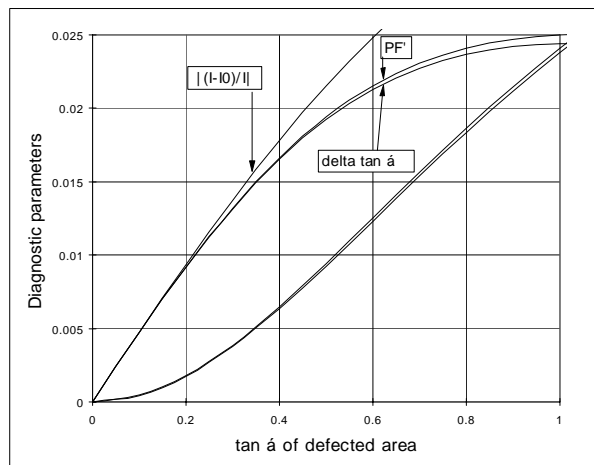
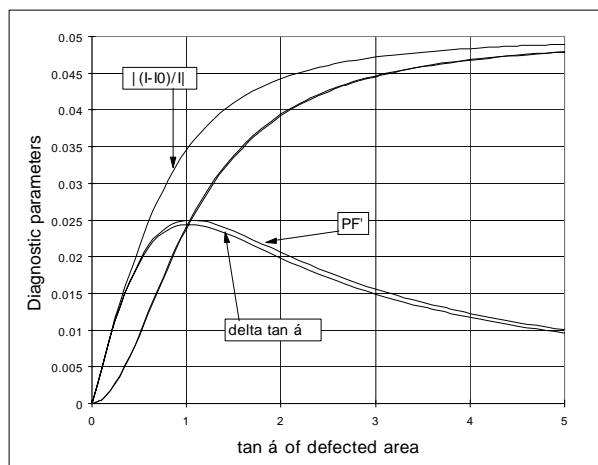
As follows from analysis, more sensitive parameters at early stage of defect developing are:

1. Imbalance current and (or) modulus of relative change of the bushing leakage current.
2. Relative change in losses.
3. Change in $\tan \delta_1$.

At stage of developed fault the more sensitive parameters are:

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

One can emphasize that the most fruitful method of detection and identification of the local defect of the core is On-Line measurements of modulus of imbalance current.



Comparative Sensitivity of Diagnostic Parameters to Local Defect in the Core
FIGURE 1

EVALUATION OF FAILURE MODE INVOLVED DETERIORATION OF BUSHING OIL

Possible Mechanism of Failure

Discharges across the inner part of the transformer end porcelain are outcome of a typical aging-mode phenomena in the bushing. The failure process is initiated and developing within the oil channel between the core and lower porcelain.

Electric field intensity in the oil channel and across the surfaces of core-end components and inner porcelain is established both by the bushing insulation design and by disposition of the bushing end relative to the grounded parts and the winding.

The failure process which was partially described in ^{9, 10, 11, 12, 22, 23} may be introduced as the following:

- specific aging of oil;
- formation of oil decay product, particularly, colloid containing atoms of metals;
- coagulation of these non-uniformities and deposit of semiconductive sediment on the surfaces;
- reducing dielectric strength of oil;
- change in distribution of voltage along the porcelain;
- appearance of discharge in oil, particularly, under action of switching transient, gas generation;
- surface discharges, flashover

EFFECT OF SOME FACTORS ON FAILURE DEVELOPING

Electrical Effect of Bushing Installation

- Approach the bushing end to the grounded components can increase field intensity by 20-25% and essentially distort the inner field picture
- In some cases, e.g., in some design of shunt reactors, a large stressed volume of oil is set up, which is very sensitive to oil contamination
- Spare margin of dielectric strength of the bushing integrity determines by dielectric strength of the oil channel between the core and porcelain
- Reducing dielectric strength of oil can critically reduce the margin and cause partial discharge activity
- Electrical field impacts on chemical reactions in oil and favors coagulation of colloid

Thermal Effect of Transformer

- Heat torch which is radiated from transformer determines air temperature around the air-end of the bushing.
- Transformer oil is the main source of bushing heating. Another two sources are dielectric losses in the core and resistance losses in the central conductor. The latter does not effect essentially on temperature distribution if bushings current is less than 50% of rated.

- The basic heat exchange is expected to be in the oil channel between the core and porcelain. Specifically close to the bottom of the mounting tube approximately on the level of top oil of transformer, where principal mass exchange takes place. Here convection flow turns down close to the surface of the core. The maximal temperature of bushing oil in some place can be equal to the top oil temperature or even above that.
- Specific process of bushing oil cooling favors formation of colloids.

DEFECTIVE CONDITION

Results of investigation condition of several thousands 110-750 kV bushings including several hundreds units which were dismantled for inspection of condition of the core and internal surface of porcelain have shown the following marked signs of defectiveness:

- Increasing dissipation factor of oil up to 5-60% at 90 °C
- Reducing dielectric breakdown, particularly, in the samples taken from the bottom
- Appearance colloids containing atomic metals (copper, aluminum, zinc, etc.)
- Appearance of combustible dissolved gasses, what is typical for PD in oil
- Deposit of oil decay on the core and low porcelain. Discoloration of the porcelain: from light yellow to dark brown color. The sediment can be wiped out.
- Traces of discharges like trees across the porcelain surface, sometimes with glaze damage.

Special checks of bushing removed from service due to excessive value of $\tan \delta$ of oil have shown that they can meet high voltage routine test specified for new bushings.

E.g., three 150 kV bushings which had had $\tan \delta$ oil 70-100% and (as was revealed after the test) typical deposit coated low porcelain surface stands successfully 1 min. AC test of 375 kV.

DIAGNOSTIC CHARACTERISTICS

At the first stage of fault developing : deteriorated oil, porcelain contaminated with semiconductive sediment:

- dissipation factor and resistivity of the oil
- appearance of colloid (change in optical characteristics)
- change in dissipation factor of Test Tap - $\tan \delta C_2^*$, particularly, with temperature
- reducing $\tan \delta C_1$ with temperature rise
- change in imbalance current

At the second stage: appearance of discharges across the porcelain:

- appearance of combustible gasses being typical for PD or surface discharge in oil
- reducing $\tan \delta$ down to negative value
- increasing imbalance current

EVALUATION OF DETERIORATION OF THE OIL USING THE TAP INSULATION C_2^* TEST

The insulation space between normally grounded tapped layer and ground sleeve is typically composed from thin support paper layer wrapped around the tapped layer and oil channel.

The equivalent circuit can be introduced as series connection of the impedance of the paper layer and the impedance of the oil.

Correspondingly, the equivalent dissipation factor $\tan \delta C_2^*$ tested by GST-Guard Test Circuit can be expressed as

$$\tan \delta C_2^* = K_p \cdot \tan \delta_0 + K_0 \cdot \tan \delta_p + \sum \tan \delta_{\text{int}}$$

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

$$K_p = \frac{C_p}{C_p + C_0} \quad \text{- relative capacitance of the paper}$$

$$K_0 = \frac{C_0}{C_p + C_0} \quad \text{- relative capacitance of the oil}$$

$$K_p + K_0 = 1$$

$\sum \tan \delta_{\text{int}}$ - additional loss factor due to possible contamination of the tap insulator, upper porcelain and external interferences.

Typically $K_0 \cong 0.1 - 0.2$, influence of interferences can be removed so that $\tan \delta C_2^*$ should be determined practically by $\tan \delta_0$ of the oil.

Correlation between deterioration of oil and $\tan \delta C_2^*$ was demonstrated in special experiment.

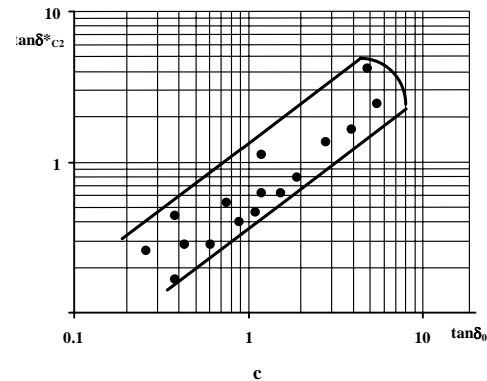
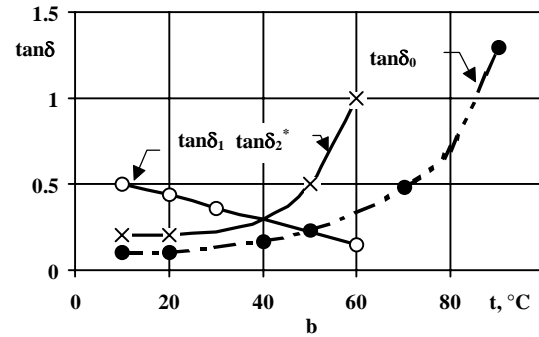
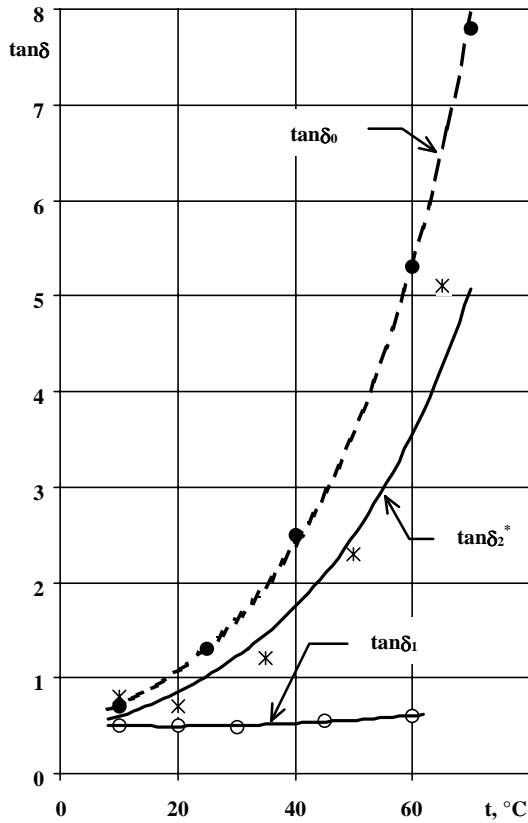
Six bushings rated 150 kV, 2000 A, equipped with Test Tap, after being in service 12-13 years had been tested to investigate change in dielectric characteristics with temperature. The bushings had different degree of oil deterioration and different degree of lower porcelain internal discoloration from light yellow up to dark brown (this condition was evidential after dismantling) due to deposit of oil decay.

The mounting flange of the bushing had been isolated from the grounded components to provide using UST test circuit technique. The bushing had been heated in steps up to 70-75 °C by means of hot air. Dielectric characteristics C_1 and C_2^* have been tested at the certain temperature step.

In Figure 2 are shown the plots of $\tan \delta C_1$ and C_2^* and $\tan \delta_0$ of the oil samples versus temperature for severe contaminated bushings ($\tan \delta_{90}$ above 15%, dark brown deposit on inner porcelain) - Figure ***, then for a little contaminated bushing ($\tan \delta_{90} = 1.0\%$) - Figure 2 and correlation between $\tan \delta C_2^*$ and $\tan \delta_0$ of oil for all six tested bushings.

It was found that $\tan \delta_{C_2^*}$ follows legible $\tan \delta$ of the bushings oil, so that one can obviously predict condition of the oil using $\tan \delta_{C_2^*}$ value.

However, it is difficult to recognize deterioration of the oil at comparative low oil temperature, e.g. 20 °C or less due to comparable low values of $\tan \delta_0$.



Correlation between Dissipation Factor of Bushing Oil and Dissipation Factor of C_2^* Test Tap.

Effect of Temperature on Dielectric Characteristics of Deteriorated Bushings

a) Bushing with Severe Deteriorated Oil

b) Bushing with Slightly Deteriorated Oil

c) Correlation between $\tan \delta_{C_2^*}$ and $\tan \delta_0$ in the Six Tested Bushings

150 kV

FIGURE 2

ESTIMATION OF $\tan \delta$ OF THE OIL THROUGH THE DIFFERENCE IN $\tan \delta$ OF C_2^*

The following method has been suggested by ZTZ-Service²³ to estimate the condition of oil without sampling using Tap Test.

Prior to deenergizing for tests transformer is heated by inner losses (by means of reducing cooling) up to top oil temperature 60-70 °C. At some elevated temperature t_1 $\tan \delta_{C_2^*}$ is measured. Then temperature of transformer oil is reducing by 20-30 °C by

means of switching cooling for a time, and the second value of $\tan \delta_2 C_2^*$ is tested at temperature t_2 .

If paper insulation is dry (or not too wet) ($K_0 \tan \delta_p$) is of a little value and does not effected significantly by temperature. Therefore,

$$\Delta \tan \delta_{C_2^*} = \tan \delta_1 C_2^* - \tan \delta_2 C_2^* \cong (\tan \delta_{10} - \tan \delta_{20})$$

From this equation:

$\tan \delta_{10}$ - dissipation factor of oil at t_1^0 can be defined as

$$\tan \delta_{01}(t_1) = (1 + \alpha) \cdot K (\tan \delta_{1C_2^*} - \tan \delta_{2C_2^*}),$$

$$\alpha = C_0 / C_p$$

$$\text{where } K = \frac{1}{1 - e^{-\beta(t_1 - t_2)}}$$

$$\beta = 0.04$$

Nearly of 8 years experiences have confirmed effectiveness of this approach.

In Table IV some results with estimation of oil condition in the 110-500 kV bushings are presented. One can see a good correlation between estimated data and meanings of $\tan \delta$ of oil measured in the samples.

Thanks to above mentioned method e.g in Power and Distribution Corporation Kievenergo over 30 defective bushings were detected and replaced. Further investigation of the condition of those bushings has confirmed severe deterioration of oil, discoloration of the inner porcelain, and in 7 bushings - traces of surface discharges across the porcelain revealed.

TABLE IV

Estimated Data of $\tan \delta$ of Oil in the 110-500 kV Bushings Equipped with Test Tap through Difference in $\tan \delta C_2^*$ Measured at Two Temperatures

No	Types of Bushing	Bushing oil temperature		$\tan \delta C_2^*$		$\tan \delta$ of the oil at 70 °C	
		t_1	t_2	t_1	t_2	estimated	in the sample
1	110 kV 2000 A $\alpha = 0.11$	51	37	1.7	1.5	1.1	0.45
2		51	37	5.3	2.5	15.5	9.3
3		30	24	3.8	2.9	23.2	18.6
4		30	21	3.2	2.3	16.3	11.6
5	150 kV 630 A $\alpha = 0.1$	48	29	4.0	1.3	13.5	16.3
6		49	34	6.9	4.2	15.3	10.0
7		49	34	6.2	3.2	16.9	9.8

8	500 kV, 1600 A $\alpha = 0.11$	40	32	0.92	0.51	5.6	2.5
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ESTIMATION OF THE BUSHING'S OIL TEMPERATURE

Convective movement of oil within a bushing depends on the width of oil channel between the core and porcelain housing and mounting tube.

In case of a capillary size of the channel (a few millimeters) the axial movement of oil is impossible and temperature of oil within transformer part and air part of the bushing are essentially different: within the lower part oil temperature is close to that of the transformer top oil (T_{ot}) temperature or above it, within the air part oil temperature is close to air temperature around the bushing (T_a).

In case of a greater size of the oil channel (a centimeter or more) the axial movement of oil can exist. Two convective oil flows can be recognized: lower flow - along the inner porcelain up to lower part of the mounting tube, where oil is cooled significantly and part of oil flow turns down along the core; upper flow - above the upper part of the mounting tube along the porcelain and core surfaces.

So, an appreciable part of the core is washed over with oil of nearly the same temperature which may be introduced as an average temperature T_0 and expressed as:

$$T_0 = T_l + (1 - \alpha)T_t + \alpha T_e$$

where $T_l = \frac{p_l}{G}$, p_l - the sum of resistance and dielectric losses in the bushing, G -

thermal conductance of the lower part of the bushing; α - is relation of thermal conductances of upper and lower parts of a bushing including the contribution supplied to them by thermal resistances of oil and air layers contacting the inner and outer surfaces of a bushing; T_a - is the temperature of the ascending flow of air above the transformer tank (the thermal torch). This temperature is intermediate between the temperatures T_a and T_{ot} , where T_e is the temperature of external air (at some distance from the transformer). T_e may be got by the direct measurement or calculated (which is less reliable) from the following expression:

$$T_e \cong \frac{T_a + \beta T_t}{1 + \beta},$$

where T_a is the ambient temperature of air outside the thermal torch. The value of β depends chiefly on the velocity of ascendant air within the torch. When $T_t \cong T_a$ β tends to zero and usually, with a hot transformer, it is about 0.4-0.7. For positive centigrade temperatures of T_t it is approximately equal to:

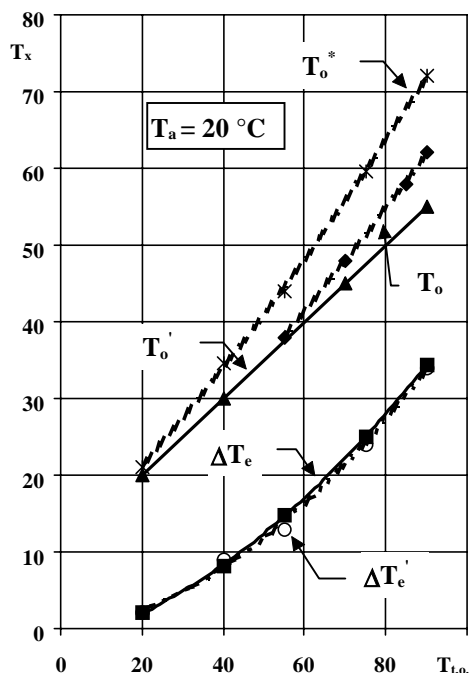
$$\beta \cong [2 + 0.1 \cdot (T_t - 20)] \cdot 0.08$$

Effect of a hot transformer on the temperature rise within a thermal torch and both effects of top oil temperature and "heat-torch" on average temperature of the oil within the bushing have been studied with 110 kV 630 A bushing ($\alpha \cong 0.5$). Some results are shown in Figure 3.

It was confirmed significant transformer's top oil and heat-torch effect on bushing behavior and found a good correlation between measured and calculated values of torch temperature and bushing oil temperature.

It was also found that within top oil temperature range 40-60 °C some simplified expression for T_0 can be used:

$$T'_0 = \frac{T_0 + T_a}{2}$$



Heat-Torch Effect of Transformer on the Average Oil Temperature within 110 kV Bushing

$\Delta T_e, \Delta T_e'$ - measured and calculated rise of the torch temperature above ambient

T_0, T_0' - measured and calculated oil temperature with excluding torch-effect

T_0^* - estimated oil temperature with heat-torch effect

FIGURE 3

DIMINISHING EFFECT OF THE TAP INSULATOR CONDITION

Contamination of the tap insulator surface causes reducing the resistance of the insulating space C_2^* and correspondingly introduces additional losses and tip-up of $\tan \delta$ C_2^* .

A special experiment with artificial moistening the insulator on the 150 kV bushing (typical values of $C_3^* = 800 - 1000$ pF) has shown the following effect of reduction of DC resistance of R_2^* :

R_2^*	$\tan \delta C_2^*$
3000 M Ω	0.5-0.7%
1000 M Ω	1-1.5%
500 M Ω	1.7-2.0%

To avoid the negative effect of the tap insulator condition DC insulation resistance prior to $\tan \delta$ test shall be measured R_2^* .

The minimal value of $R_{2\min}$ can be expressed as:

$$R_{2\min} \geq \frac{1}{\omega C_2^* \Delta \tan \delta_{in}} M\Omega$$

where $\omega = 2\pi f$

$\Delta \tan \delta_{in}$ - permissible arrow

Assuming $\Delta \tan \delta \leq 0.2\%$, $C_2^* = 1000 \text{ pF}$, $f = 60$ one can determine $R_{2\min}$ as

$$R_{2\min} > \frac{10^{12}}{2\pi 60 \cdot 1000 \cdot 0.2} \cong 1300 M\Omega$$

EVALUATION OF CONTAMINATION OF THE INNER PORCELAIN

Increasing conductivity of inner porcelain due to coating with semiconductive deposit and appearance of creeping discharges are characteristics inherent to defective condition of the bushing.

Appearance of surface current effects on dielectric characteristics of the core through partial capacitance between conductive layers and porcelain.

There are a number of uncertainties relative to size of contaminated area and value of conductivity of contaminant. Therefore, one can expect vague effect of porcelain surface contamination. dependivе to contamination pattern $\tan \delta C_1$ can increase or decrease down to even negative value.

However, service experience has shown that in the most cases semiconductive deposit on the porcelain results in reducing $\tan \delta C_1$.

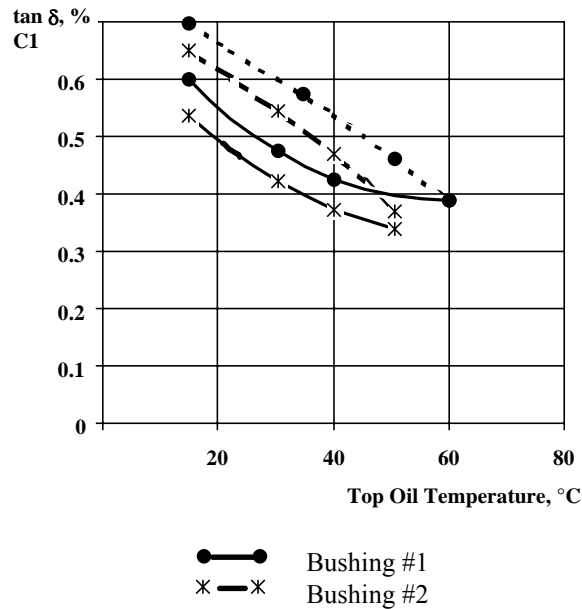
E.g., investigation of the condition of 500 units 150 kV bushings in one of the largest Ukrainian Power Corporation "Dneproenergo" revealed ²⁴ that 40 bushings had $\tan \delta C_1$ less than 0.3%. Following test of oil showed increase of $\tan \delta$ of oil in those bushings in average up to 5.5% at 90 °C and severe discoloration of inner porcelain. In one of the bushings with negative $\tan \delta C_1$ traces of PD across the porcelain was revealed.

Two findings can be underlined:

- Effect of semiconductive deposit on reduction of $\tan \delta C_1$ is the stronger the lesser is relative value of $\tan \delta$ of oil.
- Increase of bushing temperature leads of deposit conductivity and correspondingly lowering $\tan \delta C_1$ with temperature.

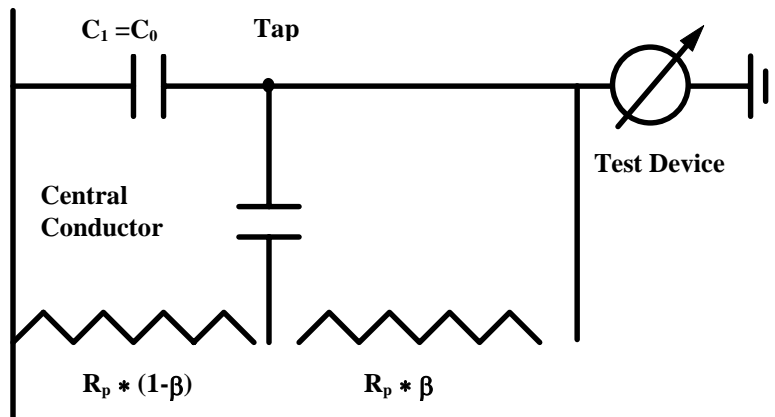
These suggestions have been verified e.g. by the tests of two 110 kV bushings which were removed from service due to detected deterioration of oil. The oil was changed, but some deposit of deterioration products remained.

In the both bushings obvious reducing $\tan \delta C_1$ with temperature was revealed. In Figure 4 one can see the plots of $\tan \delta_1$ tested at 10 kV and 73 kV (rated voltage) versus temperature.



Dissipation Factor C_1 Versus Top Oil temperature in Aged 110 kV Bushings after Changing Deteriorated Oil
FIGURE 4

Possible change in dielectric characteristics can be analyzed using the simplified circuit (Figure 5), where effect of contamination is introduced with concentrated capacitance C_p between the core and porcelain, resistance of porcelain R_p schematically defined into two parts in $\frac{\beta}{1-\beta}$ proportion, when $0 < \beta < 1$.



Equivalent Circuit of Contamination of Inner Porcelain
FIGURE 5

Relative change in the modulus current in the circuit is equal to

$$0 \leq I_0^* = \frac{\gamma}{\sqrt{1 + \tan^2 \delta_p}} < \gamma,$$

where

$$\gamma = \alpha \cdot \beta,$$

$$\alpha = C_p / C_0,$$

$$\tan \delta_p = \omega R_p \cdot C_p \cdot \frac{\beta}{1 - \beta} \quad \text{- power loss factor of the surface}$$

Capacitance C_p is of the order of 10 pC, so that α is of the order of 0.02 On assumption $\beta = 0.5$,

$$\gamma = \alpha \cdot \beta = 0.01.$$

Therefore, we can expect change in imbalance current due to deposit of contaminants by the value of the order of percents. Appearance of discharges can enhance rise of current.

Experience has shown that in some cases arising imbalance current had been proceeded due to surface contamination.

CASES OF HISTORY

Detection of Excessive Water Content

In 1996 experts of ZTZ-Service have investigated the condition of 7 autotransformers 200-250 MVA, 220/110 kV installed in NEK (Bulgaria) after 22-23 years of service with the goal to assess and extend the life.

A special task of Life Assessment Program was evaluation of the condition of unsealed type 110 kV bushings in which excessive water content was suspected. The PF C_1 - temperature technique with M4000 device was used. The bushings were preliminary heated with transformer oil heat and dielectric losses. Thanks to M4000 facilities it was possible for a short time to evaluate bushings condition at three different temperatures.

- Case 1. Bushinh 114 kV, 1640 A, equipped with Test Tap. test result UST-R circuit:

T_a °C	T_{t0} °C	U_{kv}	I_{mA}	Watts	PF%	C_1 pc
22	29	10	1.1	0.268	2.43	350.1
26	45	10	1.109	0.465	4.2	352.8
26	65	10	3.7	1.495	8.24	359.4

Elevated value of PF_{C1} and characteristics rise with temperature were symptoms of water content about 5%²⁶. Some increase of C_{hot} / C_{cool} ratio corresponds to the image of defect.

Samples of oil taken from the bottom of the bushing has confirmed water contamination of the bushing:

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, equipped with test Tap.

Test / Circuit	T _a	T _{t0}	Watts	PF%	C _{pc}
C ₁ /UST-R	23	26	0.082	0.73	393.5
	21	50	0.233	1.88	408
	29	65	0.492	4.04	403.4

Estimated water content in paper was 3-4%, however, slop of PF versus temperature¹¹ more sleeper than should be for just wet insulation. Some dielectric overheating and appearance of additional losses was suggested. DGA results appears to confirm this assumption (elevated CO, low ratio CO₂ / CO, elevated C₄H₁₀ (butane-1) as characteristic of low temperature overheating):

H ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO	CO ₂	ΣC ₃	C ₄ H ₁₀
28	38	20	37	no	754	1921	130	2381

Water content in the oil sample - 30 ppm.

DETECTION OF IONIZATION-MODE LOCAL DEFECT IN THE CORE

- Case 3. Autotransformer 250 MVA, 400/110 kV, MNF. TRO (AEG) BERLIN), phase C.

Bushing 420 kV, 1250 A, sealed with permanent oil excessive pressure, equipped with Test Tap. PF test with M4000 in 1996 revealed a fault in phase C.

Test results (UST-R)

T _a	T _{0t}	kV	PF%	C ₁
25	38	10	1.91	342.7
25	54	10	2.03	343.4
25	72	10	2.11	343.5

Tip-up of PF with voltage steps was revealed too:

kV	2	4	6	8	10
PF _{C1}	1.330	1.526	1.668	1.79	1.91

In 1995 similar test of T_a = 24, T₀ = 37 °C was PF = 0.353, C₁ = 337.67
Increasing PF_{C1} relatively by 1.56-1.78%, practically independence PF with temperature and some increase
of Δ C₁ / C = 0.7 were recognized as symptoms of ionization-mode fault in the area between 2-3 layers.

DGA analysis in the ZTZ-Service laboratory confirmed availability of discharges of high energy.

H₂ gas lost	CH₄ 16	C₂H₆ < 1	C₂H₄ 29	C₂H₂ 60	CO 61	CO₂ 361	ΣC₃ 15	C₄H₁₀ 55
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The defective bushing was replaced.

- Case 4. 750 kV, 320 Shunt Reactor bushing, equipped with On-Line monitoring of imbalance current (ΔI^*).

Change of imbalance current by 54 mA (or 61% of the initial leakage current) during 10 hours set up action of alarm system and tripping reactor out of operation.

Analysis of On-Line diagnostic parameters and assessment of defected area showed probability of damage of more than 40% of the core.

10 kV tests have shown: change in $\tan \delta_a$ from 0.4 to 1.13%, change in capacity from 650 to 678 pC (by 4.3%).

Local defect with short-circuit some layers was confirmed however in evidentially smaller area.

DGA analysis confirmed PD-mode destruction of oil-paper insulation.

H₂ 510	CH₄ 540	C₂H₂ 1400	C₂H₄ 230	C₂H₆ 80	CO₂ 1400	CO 710
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After dismantling the core trace of discharge between 41-90 layer (out of total 126) was revealed.

Apparently 10 kV test voltage was too small to maintain ionization process in all damaged area.

DETECTION OF OIL DETERIORATION THROUGH PF TEST TAP - TEMPERATURE TEST

- Case 5. Autotransformer 200 MVA, 220/110 kV. Bushing 200 kV, 2000 A, equipped with test tap M4000 test results.

Test/Circuit	T _A	T _{t0}	PF%	C pC
C ₁ /UST-R	21	27	0.44	561.6
	22	46	0.39	562.6
	29	20	0.038	564
C ₂ * /GAR-R	21	27	0.7	916
	22	46	1.31	914.6
	29	70	2.24	915.8

Test results have shown symptoms of increase of dielectric losses in the oil channel. Contamination of the inner porcelain was suggested also because of trend to reduce PF C_1 with temperature.

Estimated values of PF of all through Δ PF C_2^* were 2.05% at 70 °C and 4.5% at 90 °C. Power factor of the oil sample measured in ZTZ-Service laboratory was the following:

t °C	30	50	70	90
PF%	0.25	1.37	2.5	5.15

Signs of colloids were established in the oil sample.

DETECTION OF CONTAMINATION OF THE INNER PORCELAIN

- Case 6. Autotransformer 250 MVA, 500/110 kV. Bushing 500 kV, 1600 A with potential tap, equipped with On-Line monitoring of imbalance current. The system responded to two levels of imbalance current: "Alarm Signal" - 6.5% of leakage current; "Switching off" - 24% of leakage current.

The fault in the bushing was developed during 4 months after positive maintenance test. The only symptom of defective condition was increasing imbalance current 10 days after prior failure. During 5 days ΔI^* increased from initial level 0.7% up to 1%, then after 4 days up to 1.5% and up to 1.8% one day prior failure. Three minutes prior to failure imbalance current increased alarm level 6.5%.

Evidence of deposit of oil decay products and traces of surface discharges on the inner porcelain were revealed.

- Case 7. Autotransformer 333 Mva, 750/330 kV. Bushing 750 kV, 1000 A with potential tap, equipped with On-Line monitoring system, 20 years in service.

The goal of the test was evaluation of dielectric characteristics on condition of severe external field interferences using line frequency modulation system of M4000.

Test Results

Test /Circuit	T₀	T_{0t}	kV	mA	W	PF%	C pF
C_1 /UST-R	17	41	10	1.669	0.04	0.24	531.4
	14	60	10	1.674	0.245	- 1.46	532.7
C_2 /GAR-R	17	41	10	159.6	6.748	0.42	508.20
	14	60	10	160.1	8.054	0.5	509.70

Appearance of negative PF with increasing bushing temperature was recognized as a symptom of the inner surface contamination. Taking into account that there was not any insulation failure with this type of bushings it was decided to leave bushing in operation under observation of On-Line monitoring system until summer 1997.

CONCLUSIONS

1. HV bushings remain as one of the weakest transformer component which cause up to a third part of general number of Large Power Transformers failures. Probable, failure modes of bushings depend on the manner of bushing installation within transformer, as well as bushing design. The typical defects are: local faults developing in the condenser core; deterioration of oil followed with discharges across the inner porcelain and overheating the conductor contacts.
2. Irrespective of nature a local defect in the core can be introduced through dielectric parameters of the relative defected area. Image of defect can be determined through dielectric parameters of the core measured as Off-Line (power factor, change in dielectric losses, relative change in capacitance), as well as On-Line (relative change in the modulus of leakage current, modulus of the relative change in leakage current, relative change of imbalance current of three phase bushings system). All diagnostic characteristics shall be analyzed in coordination. At early stage of defect developing the most sensitive parameters are: imbalance current as modulus of relative change in the leakage current, relative change in losses, power factor. At stage of developed fault the more sensitive parameters are: imbalance current or modulus of relative change in the leakage current, relative change in leakage current, relative change in capacitance.
3. Aging of the oil in the bushing and appearance of incipient fault depend on temperature conditions in the oil channel between the core and lower porcelain and on sensitivity of dielectric strength of the bushing to degradation of dielectric breakdown of oil. Thermal and electrical effect of the transformer itself on bushing condition is of importance.
4. In the bushings equipped with Test Tap dissipation factor of the oil within the bushing can be estimated through the difference in dissipation factors C_2^* tested at two temperatures.
5. Contamination of inner porcelain can be detected through temperature behavior of $\tan \delta C_1$ namely reducing with temperature.
6. On-Line monitoring imbalance current, dissipation factor and leakage current can cover high part of the probable defects in the HV bushings.

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

DIAGNOSTIC PARAMETERS	DESIGNATION	EXPRESSION THROUGH PARAMETERS OF DEFECT	MAXIMAL VALUE	VALUE WHICH CORRESPONDS TO MAXIMAL $\tan \delta_{1m}$	VALUE WHICH CORRESPONDS $\Delta \tan \delta_1 = 1\%$ $\alpha=0.05$, $\tau=0.2$
Change in Power Loss Factor $\tan \delta_1 = \tan \delta_1 + \Delta \tan \delta$	$\Delta \tan \delta_1$	$\frac{\alpha \tau}{(1 + \alpha) + \tau^2}$	$\frac{\alpha}{2\sqrt{1 + \alpha}} < \frac{1}{2}$ $\tau = \sqrt{1 + \alpha}$	$\frac{\alpha}{2\sqrt{1 + \alpha}}$	1%
Relative change in dielectric losses	$P_w^1 = \frac{P_w}{U^2 \omega C_0}$	$\frac{(1 + \alpha) \cdot \alpha \cdot \tau}{(1 + \alpha)^2 + \tau^2}$	$\alpha / 2$ $\tau = (1 + \alpha)$	$\frac{\alpha \sqrt{1 + \alpha}}{2 + \alpha}$	1%
Relative change in capacitance	$\frac{\Delta C}{C_0}$	$\frac{\alpha \tau^2}{(1 + \alpha)^2 + \tau^2}$	α	$\frac{\alpha}{2 + \alpha}$	0.21%
Modulus of relative change in leakage current	$\left \frac{\Delta \dot{I}}{I_0} \right $	$\frac{\alpha \tau}{\sqrt{(1 + \alpha)^2 + \tau^2}}$	α	$\frac{\alpha}{\sqrt{2 + \alpha}}$	1.02%
Relative change in leakage current	$\frac{\Delta I}{I_0}$	$\frac{\alpha(2 + \alpha)\tau^2}{(1 + \alpha)^2 + \tau^2 + (1 + \alpha)\sqrt{\alpha^2 \tau^2 + (1 + \alpha + \tau^2)^2}}$	α	$\frac{\alpha}{1 + \sqrt{1 + \alpha}}$	0.213%

Relative change in modulus of imbalance current	ΔI^*	$\frac{\alpha\tau}{\sqrt{\tau^2 + (1 + \alpha)^2}}$	α	$\frac{\alpha}{\sqrt{2 + \alpha}}$	1.02%
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