INTERNAL INSULATION FAILURE MECHANISMS OF HV EQUIPMENT UNDER SERVICE CONDITION

By

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Summary

In order to determine of efficient diagnostic system and to prevent catastrophic failures, it is critical to understand typical failure-mode and failure mechanisms of particular insulation design. This paper presents some considerations in failure mechanisms of oil-barrier transformer insulation and oil-paper condenser type insulation of instrument transformers and HV bushings on the basis of service experience and special studies.

Keywords

HV equipment-Insulaton-Discharge-Failure mode-Oil

1.Typical Failure Modes of HV transformers

Table 1 summarizes some typical defects and failure-modes of oil-barrier transformer and shunt reactor insulation and condenser type bushings and current transformer insulation that were suggested on the basis of service experience [1,2,3,] considering a wide range of equipment design and operation conditions. However actual failure-modes and failure cause can be substantially different for different insulation design. Analysis of operation experience with transformer equipment in CIS countries for the last 10 years has shown the following picture:

Power Transformers

Insulation problems involve predominantly impairment of insulation condition in service.
Excessive moisture in the cellulose insulation is inherent basically to the transformers with open-breathing preservation system or to those which have an insufficient sealing. Distribution of the moisture in the course of the transformer life is kept quite non-uniform. Most of the water is stored in so-called “cold thin structures”, namely in the thin pressboard barriers that operate at bulk oil temperature.

General “aging” problem is accumulation of conductive and polar particles in oil and depositing them on the service. Insulation surface contamination has been observed in the forms of the adsorption of oil aging products with cellulose or deposits of conducting particles and insoluble aging products in areas of high electrical stresses. The surface contamination can cause a distortion of electrical field and a reduction in the electrical strength of the insulation system.

Relative failure rate of Power Transformers 100 MVA and above in CIS countries is about 1.%. The rate of major failures is about 0.5%. About 25-30% of major failures are associated with breakdown of major and minor insulation being in service over 20-25 years due to accumulation of manifold agents of degradation. The most likely failure –modes are the following:

Occurrence of critical PD in oil due to penetration of free water through bad sealing that results in breakdown between coils typically of HV winding and breakdown of oil gap between HV winding and tank.

Flashing over HV winding under effect of switching surge and lighting impulses due to contamination surface likely with conductive particles and polar oil aging products.

Progressing creeping discharges between phases and between winding –to ground. This type of failure –mode has been observed only with some old design as a result of severe contamination of insulation with metal particles and distortion of insulation structure due to winding buckling.

Shunt Reactors 400-750 kV

The relative rate of major failures is about 1 %, and about 40% of forced outages are associated with insulation problems. The following failure modes were involved:

Flashover along the winding and traces of discharges on the barrier facing to the winding.
Flashover between pair or several coils.

Flashover along the inner surface of low porcelain of the bushing.

In many cases severe contamination of insulation with metallic-dust view particles was found. Wear of the pumps bearings, aluminum shield attrition and localized oil heating were recognized in some cases as sources of particles generation.

HV Bushings

Bushings cause about 45% of transformers major failures. Aged mode failure occurs predominantly. About 80% of failures take place after 10-12 years of service and over 30% after 20-25 years.

Core failures happen practically only with unsealed design. Two failure-modes have been suggested: ingress of free water resulting in occurrence of critical ionization at the bottom part of the core, and aging of oil paper bulk, occurrence of excessive dielectric losses, that results in thermal instability.

Experience has shown a very low rate of core failure of bushing designed with sealed preservation system incorporating overpressure bellows (about 10 cases per about 100,000 bushing population since 1971). However experience has shown also that hermetically sealed preservation system is more sensitive to residual contaminants, and occurrence of aging by-products. Special requirements shall be specified regarding to selection the proper oil, compatibility tests, processing procedures.

Unusual failures of condenser core have been observed with circuit breaker's bushings of free breading design. The problem is associated with X-wax formation at low temperature.

The main failure mode of hermetically sealed bushings involves overflashing along internal lower porcelain due to predominantly oil aging and deposit of semiconductive stain on the porcelain surface.

Current Transformers 220-750 kV

The failure rate of 220-500 kV CTs accounts for more than 60 % of the total instrument transformers failures. The rate of major failures of CT's is about 0.35%

Two failure-modes have been typically observed.

1. Ionization-mode failures that occur predominantly in wintertime. These are referred to as "cold failures." They typically happen on the "toroid shape" designs and are caused by de-impregnation of the condenser core, ingress of air and during storage, and over-saturation with air that results in bubbles evolution after fast cooling in service.

2. Aging –mode failures that have occurred after 15-25 years of service in the summer are referred to as hot failures. Those involved are typically open-breathing CTs and with hermetically sealed units filled with oil having some elevated (14-18%) aromatic content, and are caused by increased dielectric losses, followed by thermal run away and subsequent ionization process. Aging of oil, oil/paper bulk, and in some cases localized moisture contamination have been observed as the most probable life-limiting factors.

Table 1. Typical defects and failure modes in insulation of oil-immersed transformer equipment

Type of equipment/ Insulation	Typical defects and faults	Failure mode
Power Transformers / Shunt Reactors: Oil-Barrier Insulation	Moisture contamination Particles contamination; Bubbles evolution Surface contamination PD of low energy	Distractive PD Breakdown of oil Surface discharge Creeping discharge
Bushings and Instrument Transformers : Oil-paper Condenser type Insulation	Residual Moisture Poor Impregnatio Overstressing; Ingress of Moistu Ingress of Air Oversaturation with gas Aging of oil and Oill-Paper Body Thermal Instability of oil Gas Unstable Oil Copper Migration Dielectric Overheating Incipient Ionizatio X-wax deposit	Critical Ionization→ Puncture→ Explosion Thermal instability of the oil/paper dielectric→ exponential increase of dielectric losses and temperature→ critical ionization→ Explosion
Bushings: Oil/Internal Porcelain Surface	Ageing of oil Formation of metal-contained colloids/ particles Semiconductive	Critical ionization in oil Surface discharges Flashing over

	deposit Migration of bound water	porcelain
Bushings: External porcelain surface	Transformer oil contamination Picking up particles by porcelain surface Semiconductive deposit PD activity	Critical PD Flashing over porcelain

2. Failure mechanisms of Oil-Barrier Insulation

2.1 Summary of transformer models investigation

Short-Term and Long-Term tests of Aged Oil-Barrier Insulation on the basis of Life models studies have revealed the following aging-mode problems:

Reduction of Switching Surge breakdown voltage due to a deposit of insoluble aging products in areas of high electrical stress and stimulation of surface discharge occurrence [4].

The minimum breakdown voltage at switching surges may decrease approximately by 15% after aging. Increasing the concentration of particles in oil (from 50 cm^{-3} up to 160 cm^{-3}) may decrease switching surge breakdown voltage additionally by 10%.

Long-Term Dielectric Strength tests revealed two mechanisms of insulation breakdown [5] "accidental" breakdown was observed during the first period of aging due to the influence of particles and moisture; “wearing –mode” breakdown due to degradation of materials appeared at the last stage of the calculated term of aging. The latter results in decreasing the initial dielectric strength by 30-40%.

Probable cause for the reduction of electrical insulation strength is the formation of aging products, specifically, of anionic surfactants and bound water, which is not determined by the typical methods.

2.2 Mechanism of the incipient irreversible failure in oil-barrier insulation:

The first stage if incipient failure is associated with critical PD occurrence.

Mechanism of PD occurrence and progressing depends substantially of the configuration of electrical field. Presence of significant magnitude of tangential component of electric field intensity is critical to stimulate surface and creeping discharges.

Typically the failure is initiated by the breakdown of oil gap which is registered as an apparent charge in excess of 10^{-8} C that rises rapidly to 10^{-7}-10^{-6} C
It progresses in surface discharge in oil across the barrier with PD magnitude over 10^{-6} C.

“White marks» appear on the surface due to forcing oil and water out of the pressboard pores followed with carbonized “black marks” on the barrier.
PDs of 10^{-7}-10^{-6} C may cause an irreversible damage during tens of hours.

Minimum energy required to cause incipient carbonizing in the cellulose (heating over 300^0C) is estimated as 0.1 J, which corresponds to several charge pulses of 10^{-7}-10^{-6} C Stable discharge in oil associated with PD power is P>0.4 W.

An average rate of gas generation under the effect of stable PDs in oil is 50 μl/J

Further steps progress either in the breakdown of the insulation space or in the occurrence of creeping discharge.

Creeping discharge

This is, likely, the most dangerous failure mode that typically results in catastrophic failures at normal operating conditions. The phenomenon occurs in the composite oil-barrier insulation and progresses in several steps [6]:

Partial breakdown of oil gap. Surface discharge in oil across a barrier (an appearance of black carbonized marks on the barrier).

Microscopic sparking within the pressboard or between layers of pressboard sheets where gas evacuation is limited. The presence of some excessive moisture stimulates vapor bubbles forming and degradation of material.

Splitting oil molecules under the effect of sparking. The formation of hydrocarbons followed with the formation of carbonized traces in the pressboard. This process is resulted in lowering magnitudes of PD apparent charges to $5\cdot10^{-10}\cdot$-10^{-9} C however PD energy is still high enough to destruct cellulose.
Creeping process can continue from minutes to months or even years, until the treeing conductive path causes shunting of an essential

part of transformer insulation resulting in a powerful arc. The cellulose destruction while discharge progressing within the pressboard is associated with PD $q \approx 10^{-9}$ C; PD power P=0.1-1 W, average rate of gas generation of 40-50 μl/Joule.

Three critical factors could be advised to evaluate probability of creeping discharge occurrence:

Source of initial critical ionization of high energy to cause carbonized marks of the barrier;

Specific insulation design configuration

High enough dielectric stresses

Tabl.2 Conditions for creeping discharge occurrence (service experience and experiments)

Possible source of critical ionization	Gas (air) bubbles (pumps cavitations; residual air after refilling with oil; intensive local oil heating). Penetration of free water. Metal particles contamination. Local overstressing the oil gap High tangential field component across pressboard surface related with direction of insulation rolling (along the fibers)
Insulation design configuration stimulating creeping discharge progressing	Creeping path along pressboard between electrodes Winding disk-to-disk transient touch to adjacent barrier; Touch of barrier to bushing or grounded details
Conditions for creeping discharge occurrence	Magnitude of tangential component of electric field stress ≥1,0 kV/mm

2.2.2 Surface discharge

Occurrence of surface discharge is associated with increased voltage (transit overvoltage). Two mechanisms could be suggested on the basis of studies (table 3): 1) Oil breakdown progressing into insulation destruction and 2) Surface discharge as self-firing phenomenon.

A magnitude of tangential component of electric field stress that can result in PD occurrence and forcing oil out of pressboard (reversible –mode “white marks») could be suggested as criterion of dielectric strength across insulation surface. Investigation of models of unaged, dry and clean insulation has shown that surface discharge can occur under action of electric field stress 6.5-12.5 kV/mm on condition if ratio of average and maximum field intensity in oil gap is 0.4-0.5 or less.

Apparently, contamination of surface with conductive particles reduces the value of critical field intensity.

Table 3 Mechanisms of surface discharge origin and progressing. HV Power frequency tests of models

Specimen: shape of electrode; Dielectric material	**Incipient failure**	**Development of failure**
#1 Aluminum cylinder 150 mm in diameter; sharp point;-Pressboard	Occurrence of PD$\approx 10^{-10}$ C; visible luminescence; small bubbles	<u>1st phase</u> (tens seconds): unstable surface discharge of $5 \cdot 10^{-8}$C; intensive gassing; intensive luminescence. <u>2nd phase</u>: Discharges penetrate deep into the pressboard; PD intensity reduces to $5 \cdot 10^{-10}$C though intensive destruction of material goes on
#2 Aluminum cylinder 150 mm in diameter ;rounding-off radius 1 mm;-pressboard	Oil breakdown: PD of 10^{-9} –10^{-8}C; increase of PD repetition rate	Discharge progresses within pressboard, PD intensity <10-9C
#3 Aluminum toroid insulated with craft paper; rounding-off radius 9 mm;-pressboard	Surface discharges 10-7 C	Intensive gas evolution; Intensive PD> 10-7C; breakdown after 30 sec

3.Failures of bushings caused by staining off the lower porcelain

3.1 Failure mode induced by peculiar oil aging and staining of internal porcelain

Discharges across the inner part of the transformer end porcelain are outcome of a typical aging-mode phenomenon in the bushing [3]. 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.

Formation of semi-conductive residue on the inner surface of the lower porcelain has been followed and known to reduce the dielectric safety margin of the insulation space, causing a flash over across the inner surface. The failure process may be introduced as the following.

Degradation of the oil and formation of oil decay products, particularly colloids containing atoms of metals; evolution of anionic surfactants and hydrate (bound) water deposits of semi-conductive sediment on the surfaces under effect of electrical field;

Distortion of electrical field, change in the distribution of the voltage along the porcelain; reducing the dielectric strength of the oil due to transfer of bound water in dissolved state and particles [7];
Surface discharges, gas evolution, flashover

Impact of transformer design on failure stimulation
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., 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
Electrical field across the stained bushing surface attracts and picks up the conductive –mode particles out of the transformer oil.

Thermal Effect of Transformer

Heat, which is radiated from transformer tank, 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.

Peculiar process of bushing oil cooling favors formation of colloids.

Effect of oil type and compatibility of the oil with other materials

Field experience and laboratory tests of numerous bushing models have shown that significant impairment of bushings condition have been occurred practically only with acid treated oil containing relatively high aromatic carbon-hydrogen content (C_A=17%), that has shown the following properties: high hygroscopicity, an elevated content of bound water; aniline point 71^0C that promotes interaction with rubber gaskets and especially with plasticizer, inclination to form polar aging products and sludge [7].
It was shown also that oil-proof gaskets have shown different effect of oil aging acceleration. Particularly, a gasket with plasticizer can contribute to oil deterioration and promote the formation of semi-conductive sediment on the porcelain.

4.2 Failure mode induced by staining the outer surface of bottom porcelain

Experience has shown that dielectric withstand strength of the oil part of HV bushing could be very sensitive to contamination of transformer oil with conductive particles. There have been several documented cases associated with a deposit of carbon on the lower porcelain, which originated from the localized overheating of the core, and with deposits of iron particles on the porcelain surface, which originated from pump bearing wear. Formation of metal-contained colloids resulting from aging of oil with rubber and transformer metals has been observed also as a typical origin of porcelain contamination **Electrical field around the bushing stimulates picking up the particles by the porcelain (a trap effect).**

Uneven distribution of voltage along the porcelain close to the gasket joint and presence of electrical field in this area is a typical phenomenon for condenser type bushings. Maximum field intensity is located just in the vicinity of the gasket joint.
Increasing the field intensity may strengthen “a trap”-effect and result in further extension of the staining area.

The following mechanism of bushing deterioration could be suggested: forming of conductive-mode residue because of complex aging of the transformer oil in the presence of a leaching substance of rubber gasket and transformer metals. This is in combination with dissolved and suspended metals in the transformer oil could cause adherence under influence of an electrical field formed by the bushing and the grounded parts of transformer.

The difference in quality of the oil in the transformer and that used in the bushings and also some difference in oil temperature could be the main factors to explain occurrence of the formation of the stain on the outer surface only.

A local increase of the electrical field intensity in the “Bushing-Tank Wall” space could cause a concentration of conductive substances in this region. Accordingly, that could explain the formation of the semi-conductive streaks along the porcelain.

The following dangerous factors of effect of the stain should be considered:
Reduction of the porcelain leakage path (or insulating distance) and accordingly reduction of the incipient voltage of surface discharge appearance.

Mitigation of the shielding effect of the grounded shield (grounding layer) and accordingly strengthening the electrical field across the surface close to the grounding sleeve and particularly near to gasket location.

Strengthening the “trap”-effect of the stained porcelain to attract conductive-mode particles out of transformer oil.

Presence of the conductive stain on the porcelain may be introduced as “extension” of the grounding sleeve, which results in diminishing the shielding effect of the grounding layer of the core. This phenomenon may cause significant increase maximal field intensity. Accordingly, it could explain substantial reduction of the dielectric withstand strength of the bushing and possible occurrence of PD in the area close to gasket joint location of the stained bushing.

4.3 Failure of oil-filed paper insulation of non-sealed bushings of HV circuit-breaker.

When disassembling a bushing of 220 kV oil-filled circuit breaker, failed during operation, mere has been found plenty of X-wax. The failure occurred after operation for three years approximately. DGA analysis of oil samples from sister-type bushings (more than 20 pieces) has shown high concentrations of hydrogen (up to 3,5%), lower but exceeding permissible values of methane (up to 0,5%), ethane (up to 0,2%), carbon monoxide (about 0,5%). The bushings were put out of operation, and delivered to the manufacturer for investigations.

The later tests on a part of these bushings showed an essential increase in tan δ for the main insulation depending on voltage, and high level of partial discharges (up to some hundreds pC). When doing so, even at low-voltage (10 kV), the value of tanδ exceeded the nameplates values as large as 1,5 ... 2 times.

All the bushings considered above, have been filled with oil of type *GK.* In bushings filled with oil of type *T-750,* having a non-sealed construction, with an insulation construction with is quite identical to that of the bushings considered, at the same operational electric field strength, wax formation has never been detected. Therefore the cause of PD occurrence in the bushings considered shall be searched in difference in properties of \r oils *GK* and T-750. The difference in consequences of PD action on oils *GK* and T-750 are caused by the fact that oil of type *GK* has the more ability of gas emission (its relevant factor is greater by 2,5 fold than that of oil *T-75O,* therefore creation of conditions for wax formation process ^formation of gas-oil mixture) is easier in oil *GK* than in oil *T-750.* Since the value of solubility of atmospheric gases for oil *GK* is practically equal to that for oil *T-750,* there are no reasons to suppose that the cause of PD occurrence in the bushing insulation is bound up with formation of gas bubbles when changing the oil temperature.

<u>Experimental investigations of insulation specimens</u> The specimens (two little sheets of cable-insulating paper, each of them is 0,12 mm thick) were the combinations of paper and oil *FK,* having the different moisture content:

- 'dry' paper (W_p = 0,5% ... 1,0%) and 'dry' oil (W_0 - 5 g/t... 9 g/t);
- 'dry' paper and 'wet' oil (W_Q = 20 g/t... 40 g/t);
- 'wet' paper (W_p > 4%) and 'wet' oil.

The specimens were tested in sealed and non-sealed vessels. A part of specimens was at the room temperature (+20°C) all the time. The other part of them was being cooled to +5°C, -10°C, -15°C and -20°C. After cooling and exposure at this temperature, a voltage was being applied to the specimens, and they were warming within 1,5 to 2 hours. A voltage was being applied for 6 to 8 hours every day. The total time of the voltage action was equal to 50 ... 55 hours. The voltage value corresponded to that for the occurrence of steady PD (50 to 100 pC). At the voltage application, the apparent charge and the number of PD pulses were registered.

Some specimens of 'dry' paper and 'dry' oil were being naturally moistened within 1,5 month, this increased the moisture content of the oil to 25 g/t. Some other specimens were made of paper of a failed bushing, which contained moisture (about 20 g/t), wax and oil.

It was revealed that the PD inception voltage varied little for all the specimens, and was equal to 11 ... 13 kV. However PD development character essentially depends on the moisture content of specimens, temperature conditions and hermetic sealing of the device.

In the sealed vessel, irrespectively of moisture content of specimens, at cooling-wanning cycles for oil: +20°C, -20°C, +20°C> the PD development process, the location of their occurrence (the sharp edges of electrode), the number of PD pulses (about 10 ... 14 pulses per minute) and their apparent charge (900 ... 1300 pC), are the same as at the room temperature (+20 °C).

In the non-sealed vessels, when testing specimens of paper-oil insulation which were artificially moistened, at cooling-warming cycles for oil: +20°C> -20°C> +20°C, the number of PD pulses increased to 20 ... 25 pulses per minute but me values of their apparent charges were equal to 100 ... 300 pC. In these specimens, carbonised traces ofPD took place in the area of uniform field There were no traces of wax formation.

When testing the specimens which were naturally moistened, the character of PD was the same as at tests of the specimens moistened artificially. However when disassembling them, X-was was detected between layers of paper.

Therefore the supposition that moistening of oil in a non-sealed equipment followed by X-wax tonnation can be the cause of PD occurrence in paper-oil insulation in uniform field, has been confirmed.

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