A2
Power transformers and reactors

Transformer bushing reliability

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Transformer bushing reliability

WG A2.43

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Executive summary

CIGRE Working Group A2.43 Transformer Bushing Reliability was formed in 2010. The essential aim of this WG is a contribution to the improvement of HV bushing reliability (≥ 72,5 kV). Attention is given to:

- Bushing in service failures and bushing failures during transformer acceptance tests
- Failure mechanisms of various bushing insulation types
- Impacts on bushing failure rate (design, testing, service condition, maintenance and condition monitoring)

Basic principle of data collecting has been a survey based on appropriate questionnaires. Several questionnaires have been developed by the WG A2.43. In total, 70 responses have been received from 22 countries. This work is in a certain way a continuation of WG A2.37 Transformer Reliability Survey in the specific field of transformer bushings.

Bushings are an essential component of transformers. Without bushings, large power transformers are unthinkable. A failure of any of the bushings results in a transformer failure as well. According to various researches, bushings cause 5 to 50 % of the total number of transformer failures, often followed by transformer damages, fires, huge collateral damage and ecological incidents. A bushing's main roles are to conduct and electrically insulate. However, the function of dividing different insulation media is of the same importance because the bushing plays a significant role in determining the oil-filled transformer fire protection properties. HV bushings are thin and fragile structures, sensitive to mechanical forces, earthquakes or vandalism and they are normally mounted on the hottest part of the tank, exposed to atmospheric and environmental conditions. Electrical field strength in the bushing condenser body is among the highest in HV technology. All of these factors influence bushings condition and reliability.

Bushing theory, their parts, insulation types (RBP, OIP, RIP and RIS), electrical field grading types as well as their basic properties are explained in this brochure. How bushings influence transformer reliability and some essential facts about HVDC bushings are also provided.

Bushing failures are rarely analysed separately from transformer failures. The consequence is that only terminal bushing failures (defined as where major transformer damage occurs) are normally analysed because of their large impact on the transformer. The approach laid out in this brochure is an attempt to expand bushing failure research so that besides terminal failures, the incipient bushing failures (or non-transformer-damaging) are also included. In the questionnaire part related to in-service failures, 240 bushing failures were collected on more than 101.000 in service bushings. About 30 % of the collected failures were terminal. Another questionnaire topic was related to bushing failures during transformer factory acceptance test. 99 bushing failures were collected among 44.000 bushings tested or a failure rate of 0,23 % was obtained. Data regarding bushing diagnostic practices within utilities were collected also.

Various bushing failure mechanisms for all bushing insulation types are grouped in four essential phenomena: mechanical, thermal, electric and dielectric, as well as chemical and pollution. These led to a certain failure scenario, that are described and supported with case studies. Mitigation measures are suggested. Failure scenarios explained in this brochure have been gathered through WG members, experience and references, and we hope that they are representative for bushings worldwide.

To prevent failures, bushings are subjected to condition diagnostics: off-line (periodic) and on-line (continuous). The majority of these diagnostic methods, traditional or recently developed, are explained in detail. For each method, physical and measurement basics, condition decision criteria, the effectiveness and limitations are provided. Today, with development of bushing on-line continuous monitoring systems, new opportunities appear to improve transformer bushing reliability. Bushing short-term and long-term storage concerns regarding various bushing types are also discussed.

Finally, a summary of recommendations for bushing reliability improvement and changes to relevant standards is provided. Among them are the recommendation for development of condenser bushings for higher temperatures, standardization of test tap design and development of silicone upper envelope sheds resistant to animal attack.

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List of abbreviations

A2.43 – Study Committee Transformers, Transformer bushing reliability
AC – Alternating current
AE – Acoustic emission methods (for PD location and qualitative registration)
Al – Aluminium
ASEAN - Association of Southeast Asian Nations

C – Capacitance, also often used for bushing HV capacitance C1
C_0 – Capacitance at higher frequencies, (Figure 5.2.3.1)
C_1 – Bushing HV capacitance (bushing HV condenser body capacitance
C_1, C_2, $\cdots C_n$ – Dielectric polarisation capacitances, (Figure 5.2.3.1)
C_{1i} – *i*-th in line HV capacitance
C_2 – Test/tanδ/measuring tap capacitance or voltage/capacitance/potential tap capacitance
CC – Creepage current
CIGRE – International Council on Large Electric Systems (*Conseil International des Grands Réseaux Électriques*)
Cu – Copper

DC – Direct current
DDF – Dielectric dissipation factor
DFR – Dielectric frequency response
DGA – Dissolved gas analysis
DSP – Digital signal processor

EGAT – Electricity Generating Authority of Thailand

FAT – Factory acceptance test
FDS – Frequency domain spectrum

GIS – Gas insulated substations
GSU – Generator step-up (transformer)

H – Mark for high diagnostic sensitivity (method is sensitive to the related phenomena), (Table 4.2.1)
h_a – Condenser body length above flange
HC (1 to 7) – Hydrophobicity classification
h_i - Height of the i-th electrode
h_o – Condenser body length below flange increased for flange height
h_u – Height of the oil side
HV – High voltage
HVDC – High voltage direct current
h_z – Height of the air side

i – Current through real capacitance *C*
i_1, $i_{,2,}$ $\cdots i_n$ – Dielectric polarisation currents, (Figure 5.2.3.1)
i_C – Reactive part of current *i*
i_{C0} – Current through C_0, (Figure 5.2.3.1)
IEC – International Electrotechnical Commission
IEEE – Institute of Electrical and Electronics Engineers
i_R – Active part of current i
i_R – Current through R_∞, (Figure 5.2.3.1)
IR – Infra red scanning (imaging)
ITC – Individual temperature correction

k – Relative load during measurement (S/S_n)

L – Mark for low diagnostic methods sensitivity (method results are often inconclusive), (Table 4.2.1)
LF – Low frequency
LI – Lightning impulse
LV – Low voltage

M – Mark for medium method sensitivity (method is less sensitive to the related phenomena), (Table 4.2.1)
MV – Medium voltage

OIP – Oil impregnated paper (bushing technology)
OLTC – On load tap changer

p.u. – per unit
PD – Partial discharge
PDC – Polarisation-depolarisation current
PF – Power factor, $\cos\varphi$, $\sin\delta$
PLN – Perusahaan Listrik Negara, Indonesia
ppm – parts per million (volume: µl/l or weight: mg/kg)

Q1 – Bushing in service failure questionnaire
Q2 – Transformer Acceptance Test (TAT) failure questionnaire for bushings
Q3 – Bushing manufacturer failure data questionnaire
Q4 – Bushing diagnostics, maintenance and failure practice questionnaire

R – Resistance
R_1, R_2, $\cdots R_n$ – Dielectric polarisation resistances, (Figure 5.2.3.1)
R_∞ – Long time, low frequency (DC) resistance, (Figure 5.2.3.1)
RBP – Resin bonded paper (bushing technology)
R_e – Equivalent resistance; represents losses in capacitance C;
r_i – Radius of the i-th electrode
RIP – Resin impregnated paper (bushing technology)
RIS – Resin impregnated synthetic (bushing technology
RVM – Recovery voltage method (or measurement)

S – Actual transformer load
SC 12 – Study Committee Transformers
SF_6 – Sulphur hexafluoride
S_n – Rated transformer load

T – Measured temperature
$\tan\delta$ – Dielectric dissipation factor
TAT – Transformer acceptance test
t_C – Charging or polarization time, (Figure 5.2.3.9)
t_d – Discharging or depolarization time, (Figure 5.2.3.9)
T_n – Temperature recalculated to rated load and T_{om}
TNB – Tenaga Nasional Berhard, Malaysia
T_o – Ambient temperature
T_{om} – Maximal average daily temperature (according [2.1], 30 °C)
t_p – Charging or polarization time, (Figure 5.2.3.2)
t_{peak} – Time of U_{max} after removing the short (Figure 5.2.3.9)

u – Voltage at condenser C;
U – Voltage, general
UHV – Ultra high voltage
U_{max} – Maximum recovery voltage, (Figure 5.2.3.9)
UV – Kind of electromagnetic radiation - ultra-violet radiation
VFT – Very fast transient
VI – Visual inspection

WG – Working group

X-ray – Kind of electromagnetic radiation - Rontgen radiation

Δ – Prefix symbol for the difference between two quantities
δ – Angle between phasors i_C and i
ε_0 – Permittivity of empty space (vacuum);
ε_r – Relative permittivity of a material
ε_{r1} – Real part of relative permittivity
ε_{r2} – Imaginary part of relative permittivity
ϑ – Temperature rise
ϑ_{av} – Average bushing temperature
ϑ_f – Flange temperature (approx. equal to top oil temperature or tank cover temperature),
ϑ_h – bushing head temperature
ϑ_n – temperature rise recalculated to nominal load
π – mathematical constant, 3,14159….
φ – Angle between phasors i and u
ω – Angular frequency = $2\pi f$;

3D – Three dimension(al)

1. Introduction

Bushings are among the most frequent cause of transformer failure. According to the data from various researches and electric power utilities, bushings cause from 5 to 50 % [1.1] of the total number of transformer failures. Bushing failures are the most common cause of transformer fires which can cause huge collateral and ecological damages at the switchyard [1.2]. Bushings are a transformer's crucial component and one transformer can have more than ten bushings. A failure of any of them has a transformer failure as a consequence. A bushing burst damages a transformer in many different ways. An upper porcelain envelope burst launches fragments at an enormous speed and they possess a destructive power even at a distance of up to hundred meters or so. The burst of the bushing's lower part damages a transformer in such a way that the conductive and burnt debris of the condenser body contaminates its active part. Cleaning of the transformer's active part from bushing fragments is a difficult task with doubtful results.

Bushings are often mounted on the hottest part of the transformer tank and they are exposed to both the highest and the lowest ambient temperatures. This combined with external mechanical forces results in huge demands on the bushing insulation and sealing system. It should also be noted that the electrical field intensity in the bushing's HV condenser body is among the highest in HV equipment. HV bushings are a thin and fragile structure, sensitive to mechanical forces from earthquakes, vandalism and the physical connection to the switchyard.

To prevent bushing failure, they are subjected to condition diagnostics via many methods which are used with varying effectiveness.

Nowadays, beyond the bushing's classical roles, they form part of the transformer monitoring system and their tap is continuously exposed to voltage and overvoltages. This new role is a challenge for some bushing properties.

This brochure deals with transformer bushings (and for similar equipment such as shunt reactors) of system voltage ≥72,5 kV. The majority (practically all) of these bushings are condenser type.

Cable connectors are considered as a very special type of bushing which connects the transformer with an HV cable. These connectors are not the scope of interest of this WG.

Transformer bushings, their design, properties and failure analysis are not often a topic in transformer related literature (papers). One of the purposes of this brochure is to fill this gap by providing reader comprehensive and concise information about transformer bushings.

1.1. Short bushing history

Bushings are an important component of HV equipment and share their development with the transformer and other representatives of HV technology. The first bushings were a kind of solid type bushing often manufactured from porcelain with an inserted conductor. Similar bushings are still used for distribution voltages (up to the system voltage, U_m 52 kV) because of their simplicity, reliability and low price. For any higher voltage, they become impractical because of increasing size.

One of the oldest descriptions of a condenser type bushing was found in [1.1.1]. This paper deals with an "innovation" that is actually a condenser type test bushing for 200 kV, as a part of an HV test transformer built in 1906. The short but comprehensive theory of condenser type bushings is explained, including the role of inserted condenser electrodes in an electrical field and voltage axial and radial graduations. Basic comparison with similar non-condenser bushings reveals a huge advantage in favour of condenser bushings. It was stated that the currents thorough condenser electrodes are small, so they may be manufactured using very thin conductive foil, such as aluminium foil for example. This material is still very often used for electrodes in modern bushings. In comparison, the first 110 kV transformer was produced approximately 15 years later [1.1.2].

According to [1.1.3], capacitive graded bushing production started in 1908. Coarse graded first and after that fine graded, in Resin Bonded Paper (RBP) technology. This technology was limited because of the relatively high level of Partial Discharge (PD) generated in small air pockets which is inevitable in this technology. Oil Impregnated Paper (OIP) technology was established in about 1944., to fulfils the needs for higher voltages and lower PD level. In 1963, the first OIP 500 kV bushing was introduced. Around

1950, the first Resin Impregnated Paper (RIP) bushing was produced [1.1.3,1.1.4]. Today OIP and RIP bushings are produced up to the highest AC and DC levels: voltages approximately up to 1200 kV and currents up to 35 kA. The RBP bushing seems to be obsolescent but some manufacturers still produce this type of bushing for replacement of old ones. Around 1990, silicone rubber on glass fibre epoxy tube was introduced as an upper envelope with the aim to eliminate some of the disadvantages of porcelain upper envelope, [1.1.5]. Recent bushing developments are moving in the direction of applying silicone sheds directly on the RIP body and replacement of paper with inorganic material (Resin Impregnated Synthetic (RIS) technology, see chapter 2.2).

For the past 50 years fine graded condenser type bushings have been used as the only choice for higher voltages because of the much smaller diameter for the same voltage compared to non-condenser type. Figure 1.1.1. shows the difference in diameters between condenser and noncondenser bushing types (scales are practically same for both figures).

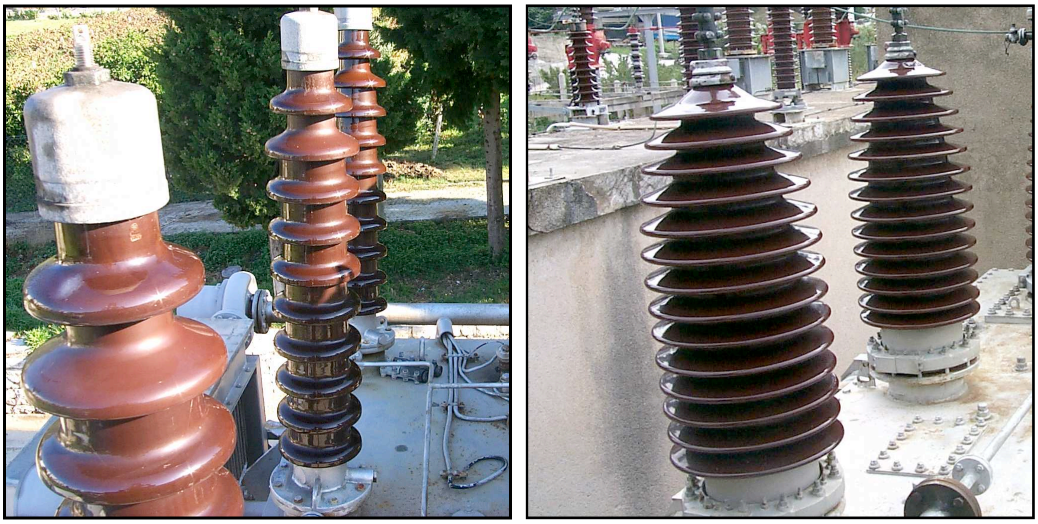


Figure 1.1.1: Condenser type bushing 110 kV, 1971. year, RBP (left); noncondenser (non-graded) type bushing 110 kV, 1958. year, ceramic (porcelain)/solid type (right)

According to [1.1.3], a 245 kV bushings in non-graded technology will have a diameter of more than one metre. A similar fine graded bushing will have a diameter of approximately 300 mm or about one-quarter of the size. Condenser core will have a diameter of approx. 150 mm (depending upon central tube diameter).

1.2. WG and brochure structure

The WG was formed in June 2010. Eleven meetings were held from October 2010 to September 2015. The group consisted of 18 members from 13 countries. According to the member's main occupation, three members belong to bushing manufacturers, two members to transformer manufacturers, seven members to utilities and six members to universities, institutes and consultants. The WG scope was divided into three task forces: TF1 - Bushing failure rate – leaders were A. Aznar and J. Brown, TF2 – Bushing failure mechanisms – leader was D. M. Geibel, and TF3 – Bushing diagnostic and monitoring.

A total of 34 presentations in the scope of the WG A2.43 were performed in 11 WG meetings:

- 20 presentations about bushing diagnostics and monitoring (experiences, new methods, ...)
- 12 presentations about bushing failures (failure modes and causes, corrosive sulphur and gaskets problems, unusual failures, ageing, overloading...)
- a presentation about Very Fast Transients (VFT) problems related to bushings
- a presentation about bushing asset management practice.

Supporting the group members, about 50 experts, from all around the world, contributed, helped and assisted the WG, especially to conduct the surveys.

The brochure is structured in seven main chapters:

- The first chapter “Introduction” with an objective and scope of work, followed by a short history of bushings. The structure of WG A2.43 and TB is also provided.
- The second chapter “Bushing description and role” explains bushing theory, bushing parts and types (RBP, OIP, RIP and RIS) and their properties. The main influences on transformers are elaborated here. This chapter is essential for understanding other parts of the brochure. It is recommended to read this first. Some essential facts about HVDC bushings are also provided.
- The third chapter “Bushing failure rate” explains and defines bushing incipient and terminal failures and their relationship to transformer failure. The experience of several utilities and international surveys are briefly presented and discussed. Four questionnaires have been prepared, promoted and analysed and the results are presented. The first questionnaire is intended for utilities regarding bushing in-service failures. The second is intended for transformer manufacturers regarding bushing failures during transformer acceptance tests. The third is about bushing manufacturer in-service failure data. The fourth is intended for utilities regarding bushing diagnostics, maintenance and failure practices. Questionnaires are given in annexures 1 to 4.
- The fourth chapter “Bushing failure mechanisms” presents bushing failure case studies divided into four basic phenomena: mechanical, thermal, electric and dielectric as well as chemical and pollution. Whenever possible, recommendations for constructional and diagnostic improvement are provided.
- The fifth chapter “Bushings diagnostics and monitoring” explains off-line (periodic) and on-line (continuous) bushing diagnostic methods. For each method, physical and measurement basics as well as condition decision criteria are provided. Additionally, a simple but effective system for bushing ranking based on bushing capacitance and dielectric dissipation factor measurement results is presented in annex 5.
- The sixth chapter “Bushing storage” deals with bushing short-term and long-term storage. Major concerns about various bushing types and their storage are discussed.
- The seventh chapter “Conclusion” a short summary together with basic conclusion are provided.

References are listed after Conclusion.

References, figures, tables and equations are numbered in a way that the first numbers represent the numbers of the chapter/subchapter and the last number represents number of the reference, figure, table or equation in a chapter/subchapter. Abbreviations are listed alphabetically, prior to Chapter 1.

2. Bushing description and role

A transformer bushing is a device through which the connection between a switchyard and a transformer winding is achieved. The bushing conducts current through an internal conductor and provides insulation between this conductor and the tank. The bushing is positioned on the border of insulation media, usually oil on the lower side, and air, SF_6 or oil on the upper side, and it separates them from each other. This feature defines, to a great extent, certain fire protection characteristics of oil-filled transformers. The bushing's main roles are:

- To insulate HV to tank
- To conduct load current
- To separate insulating media

Violation of any of the above represents a bushing failure and ultimately a transformer failure.

The main bushing's parts, performance characteristics and properties are described in relevant standards, [2.1], [2.2] and [2.3].

Condenser type bushings are produced by wrapping paper (or synthetic material) on a central tube or conductor, with electrodes (painted with conductive ink, conductive paper or thin metal foil) of certain length being inserted at certain diameters that grade radial and axial voltage stresses. Condenser type bushings consist of a large number of concentrically arranged and serially connected elementary condensers C_{1i}, Figure 2.1. One end of this condenser chain is connected to the HV central electrode and the second end is connected to the test or voltage tap. This creates two capacitances that can be measured: C_1 - HV capacitance between the central electrode and the tap, and C_2 - LV capacitance between the tap and the flange. On much older bushings, the other end of the condenser chain is simply connected to the grounded bushing flange.

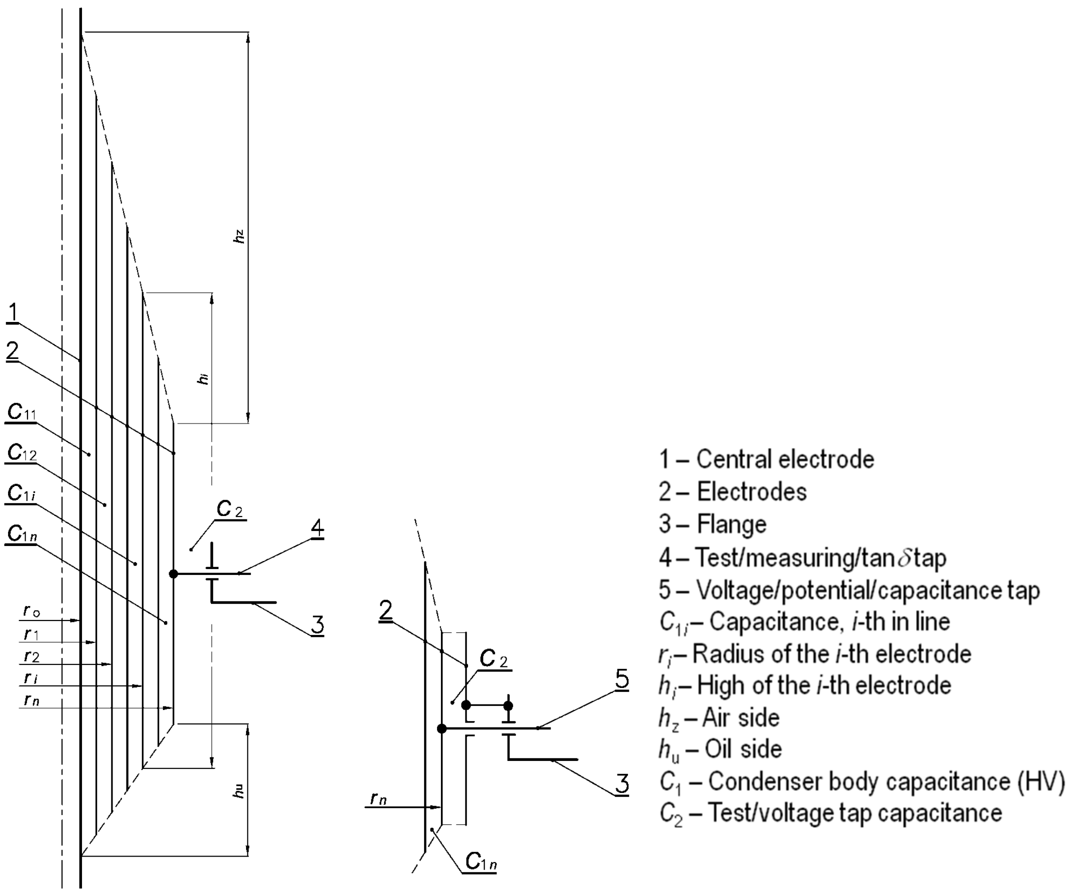


Figure 2.1: Condenser type bushing – schematic description of condenser body and test/voltage tap (left: bushing equipped with test tap, right: bushing segment describing voltage tap)

Note:

Bushing schematic description on Figures 2.1 and 2.2 (left) consider bushing fine electrical field grading technology by using only, so called, main condenser electrodes. The capacitances between electrodes are often considered to be roughly the same value (but actually they are not). Besides this often-used technology, different systems of grading technology can be used:

- So called coarse electric field grading technology with a much smaller number of electrodes. This technology is still used for gas filled bushings but is rarely used on transformers.
- Fine electric field grading technology by using of main electrodes and intermediate electrodes which are placed between main electrodes ends to ensure a more precise voltage grading, Figure 2.2 (right). The capacitance between main electrodes significantly differs from the capacitances between intermediate electrodes. This has the consequence that capacitance change corresponds to short circuited adjacent electrodes is more difficult to quantify compared to grading technology with only main electrodes.
- So called zig-zag (herringbone or fishbone pattern) technology. The idea of this technology is to apply a very large number of electrodes (refer to section 2.1.1)

The above-mentioned facts about number of electrodes and which grading technology are used play an important role for bushing C_1 capacitance diagnostics (refer to section 5.2.2).

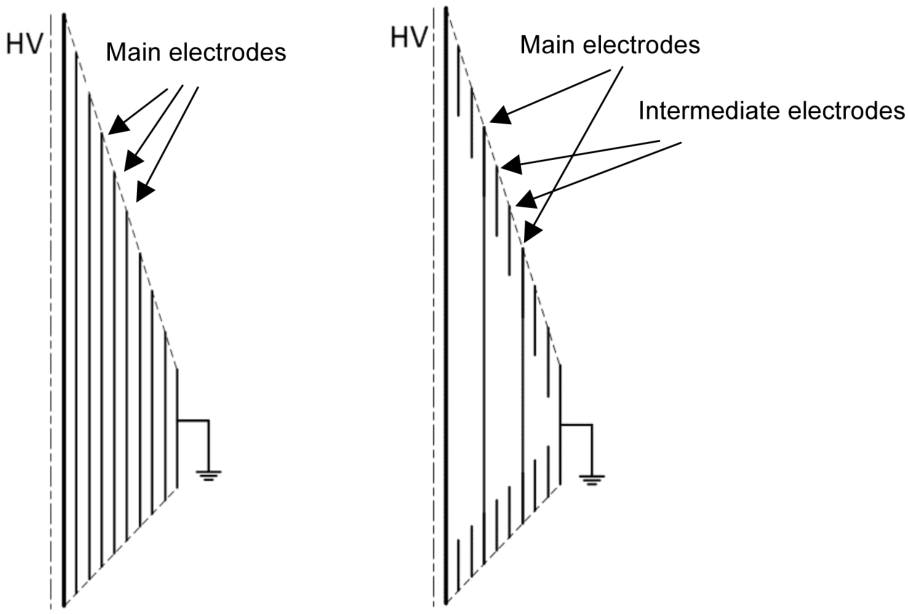


Figure 2.2: Condenser type bushing – schematic description of electric field fine graded technologies (left: with main condenser electrodes, right: with main electrodes and intermediate electrodes

According to Figure 2.1. high voltage capacitance C_1 is equal to:

$$\frac{1}{C_1} = \sum_{i=1}^{n} \frac{1}{C_{1i}} \tag{2.1}$$

Equation (2.1) shows that a breakdown of any elementary capacitance in line increases high voltage capacitance C_1. High voltage elementary capacitance C_{1i} can be calculated according to (2.2):

$$C_{1i} = \frac{2\pi\varepsilon_i h_i}{\ln \frac{r_i}{r_{i-1}}} \tag{2.2}$$

Symbols in (2.1) and (2.2) are according to Figure 2.1. C_2 of bushings with a voltage tap (also known as a potential tap or a capacitance tap) represents a capacitance between one of the last and last electrodes. It can be calculated generally in accordance with (2.1) and (2.2) by using appropriate data for C_2. C_2 of bushings with a test tap (also known as a tanδ tap or a measuring tap) is the constructional capacitance between the last electrode and the flange. For bushing mounted on transformer this include additional capacitances to the nearby grounded parts.

Contrary to widely-held opinion, the elementary capacitances of C_1 are not mutually equal. They differ not only because of technological reasons but also due to the bushing design optimization process. (There is a good example of a condenser bushing active part design in [2.4].) This fact has a drawback to C_1 diagnostics: the number of elementary capacitances in C_1 isn't enough for estimation of their capacitance change. This important information - minimum capacitance change due to a short circuited elementary condenser (or two adjacent electrodes) should be given by bushing manufacturers. Only in the case if no information from the manufacturer is available, then it is reasonable to assume that all of the capacitances between adjacent electrodes are the same.

A test tap is usually used in IEC practice, and a voltage tap is usually used in IEEE practice for bushing potential devices. The main difference between these two taps is the test voltage capability: for a test tap the rating is approximately 2 to 3 kV and for a voltage tap the rating is up to 20 kV. Accordingly, the voltage tap is much bigger than the test tap, Figure 2.3. Both should be earthed if not used in service. Rarely, a bushing can be equipped with both, a test and a voltage tap, figure 2.4 (last/earthed foil of C_2 on figure 2.1 right is connected to the test tap on the same way as on figure 2,1 left).

The test tap should be accessible from outside, if not it should be brought out to exterior in appropriate way (i.e. in the case of single flange type of oil-oil or oil-SF_6 bushings).

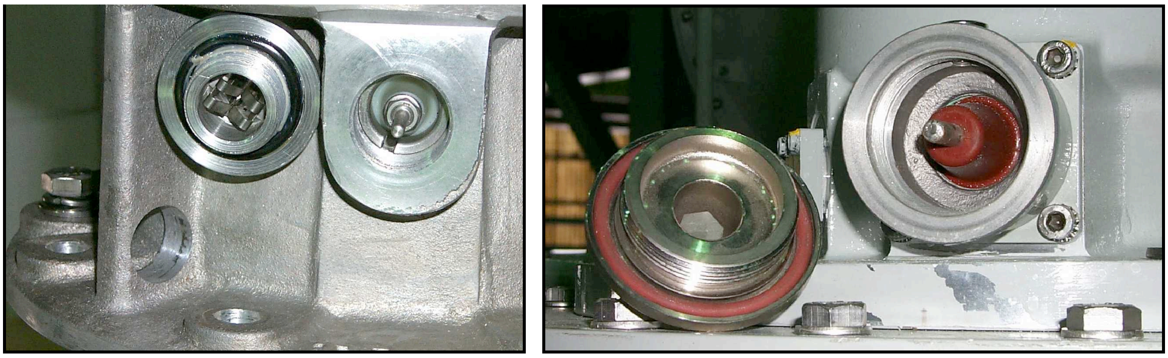


Figure 2.3: Bushing test tap (left) and bushing voltage tap (right), (examples)

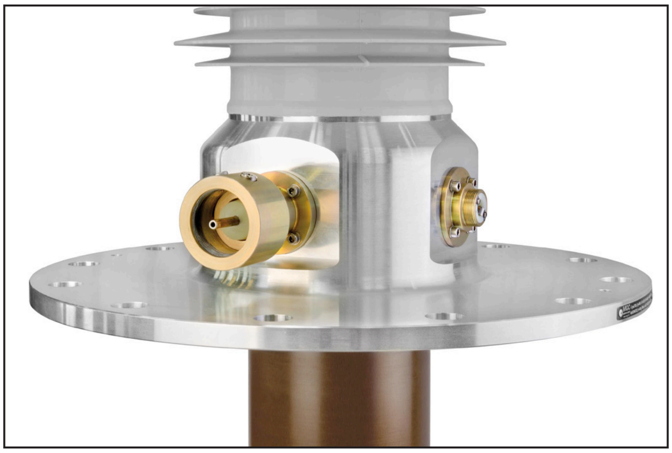


Figure 2.4: Bushing equipped with test and voltage taps (example)

It should be noted that high voltage capacitance C_1 and voltage tap capacitance C_2 are defined by the bushing's design. The influence of outside bushing factors is small and often negligible. To the contrary, the test tap capacitance C_2 is, in addition to design, influenced by many factors outside of the bushing. This is why this capacitance is much less valuable for bushing condition diagnostics than C_1, [2.5, 2.6], except in some special cases, presented in section 4.1.4.

Today, bushing test or voltage taps are increasingly used in transformer monitoring systems and thus are exposed to continuous voltage as well as overvoltages. Because of that it is recommended that in addition to tap test voltage, the maximum allowable tap service voltage (AC) and design value of impulse withstand voltage should be stated in the bushing data, refer to section 5.5.

Bushings are designed to be situated on the border of insulating media. Outside of the transformer, the media might be air, oil or SF_6. The same or different media can be inside the transformer. There are several different types of bushings meant for these differing external (to the bushing) insulation media and the most common are presented here. In the list below, the first media is inside of the transformer and the second is outside the transformer.

- **Oil-air**: these are commonly referred to as outdoor (the most often used) or indoor bushings. An outdoor bushing is shown in Figures 1.1.1, 2.1.1),
- **Oil-oil and oil-SF_6**: the visual appearance of these is almost same. Both can be single flange bushing type (tap would need to be brought out from the turret to be accessible from outside) or double flange bushing type (tap is accessible from outside).

The outdoor bushing's air-side has much larger sheds than indoor air side envelope because of exposure to environmental conditions including pollution. Bushings without sheds or with small sheds should be considered as indoor. The distance along sheds from bushing head to flange is called the creepage distance. In polluted areas, longer creepage distance (in mm/kV of U_m) is used. For example, in Figure 2.1.1, the oil part of the bushing, item 8, (without extension for current transformers, item 10), is about 3 to 4 times shorter than the air part, item. 7.

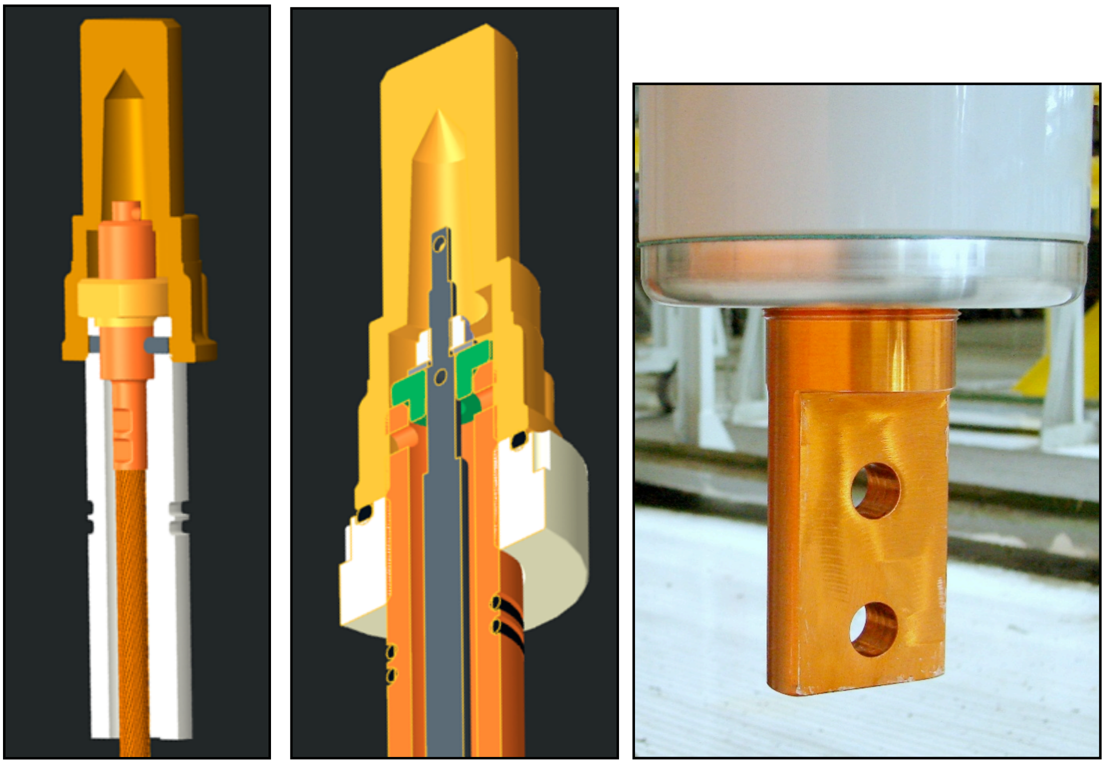


Figure 2.5: Bushing main connection (conduction) types (left: draw-lead: lead is inserted through bushing central tube, middle: draw-rod: steel rod is inserted thorough bushing central tube to maintain contact pressure, right: bottom-connected: condenser body is wrapped on the solid conductive rod)

Three main bushing connection (conduction path) types are used:

- **Draw-lead**: conductive lead (solid or rope) is inserted through bushing central tube up to the bushing head and connected to HV connection (Figure 2.1.1, item 3 and 4). Central tube (Figure 2.1.1, item 6) do not carry load current, Figure 2.5 (left).
- **Draw-rod**: a steel rod is inserted through the bushing's central tube and screwed into top connection point. The purpose of the steel rod is to apply and maintain mechanical force to join the bottom connection plate to the lower end of the central tube and in that way conductive contact between the bottom connection plate and the central tube is formed. Central tube carries the load current. This connection type is often used in North American practice, Figure 2.5 (middle).

- **Bottom-connected**: instead of a central tube, the bushing condenser body is wrapped on to a solid conductive rod that carries load current, Figure 2.5 (right).

The mentioned connection types differ in how difficult it is to replace a bushing on site (bottom connected system is the most complicated one) and in electrostatic (end) shield complexity, used for bushing end shielding. Bushings with draw rod and bottom connected systems should be equipped with a separate end shield. Bushings with draw lead systems (up to certain voltage) can be equipped with end shield built into the bushing, Figure 2.2.1, item 5.

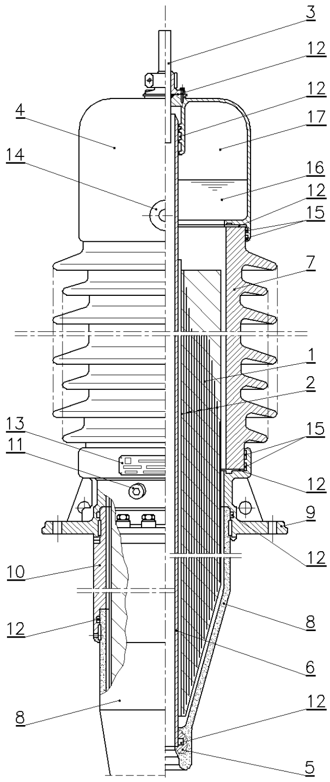
It should be mentioned that draw lead bushings can be designed without an end shield even up to very high voltage. This is called a “re-entrant” bushing, [2.7]. The lower (transformer) part of this bushing type is shorter compared to other equivalent bushings. The central tube ends above bushing lower end and below tube bushing oil part is conical in shape. This cone should precisely fit to an opposite cone on transformer lead. The clearances from a re-entrant bushing to the tank wall or turret are significantly smaller compared to the same voltage bushing equipped with an end shield. Today, this bushing type seems to be obsolete, mainly because of the small required tolerances between the bushing and the leads cone. Re-entrant bushings are expensive, complicated and very difficult to assemble on a transformer.

2.1. RBP, OIP and RIP bushings: similarities and differences

Bushings are produced in three basic types of technology: RBP (resin bonded paper), OIP (oil impregnated paper), and RIP (resin impregnated paper). For all three technologies paper is the essential material. Today paper tends to be replaced with synthetic materials with higher operating temperatures and lower humidity absorption. This new bushing type is known as resin-impregnated synthetic (RIS).

Condenser bodies are schematically almost identical for all three bushing technologies, Figure 2.1.1, but their physical features differ. Condenser bodies of RBP and RIP represent solid products which are processed by turning (machining). They mechanically adhere firmly and tightly to the flange so in this manner and with their integrity, they separate transformer oil from the surrounding medium. Therefore, the lower envelope is not necessary, because the body itself fulfils this task. In the case of condenser body breakdown, the integrity of the body and its sealing effect on the flange is usually preserved well enough to prevent the oil from leaking from the transformer, but, nevertheless, in a certain percentage of failures, leakage does occur. Consequently, this causes transformer fires because the oil leaks right onto the glowing hot bushing parts, heated due to the breakdown. In the case of OIP bushing, the situation is essentially different. There is no effective sealing of the condenser body to the flange, so in the case of a fracture of both lower and upper envelopes, oil leaks from the transformer, often leading to fires. In the case of the upper envelope fracture, oil will not leak from the transformer because the lower envelope is fixed (cemented) to the flange and the sealing effect is preserved. This significantly improves transformer fire safety. In some older versions of OIP bushings, the sealing effect was assured by the axial force, so the fracture of at least one envelope would cause oil leakage from the transformer, [2.1.1]. It is interesting to note that the transformer shut-off valve, which serves the purpose of preventing oil leakage from the conservator in case of tank rupture, often does not fulfil its role, due to the slow rate of oil flow when the bushing failure occurs. Adjusting the shut-off valve for a lower flow rate may lead to false transformer trips caused by the sudden cooling of the transformer.

The upper bushings envelopes contain sheds to ensure satisfactory creepage distance and are made of porcelain or composite materials, such as glass epoxy tube with silicone sheds, or recently, silicone sheds are applied directly on the RIP or RIS body. The porcelain upper envelopes are heavy with low elasticity, making these bushings durable but breakable. They usually burst during bushing breakdown and may rupture in the case of an outer flashover or vandalism. Their hydrophobicity is reduced in the polluted atmosphere, but this may be increased by application of a coating. Composite upper envelopes, on the other hand, are light with much higher elasticity, mechanically tougher, and more resistant to vandalism. They do not burst, and their hydrophobicity is better because of the silicone sheds, but they are considered to be less durable than the porcelain ones (hydrophobicity reduces with service especially in maritime conditions). They are sensitive to various animal attacks (rodents, birds, monkeys, …) both in-service and during transport or storage as described in section 4.1.4. and chapter 6. Silicone sheds are subject to organic attack (moss/algae/fungi) are reported but without known failure cases related to this phenomenon [2.1.2]. RBP and, especially dry types RIP bushings can operate for some time even if the upper envelope breaks. Due to greater toughness of the condenser bodies, RBP and, especially, RIP bushings have generally better seismic characteristics than OIP bushings. It should be noted that recent OIP bushing development improves their seismic properties.



OIP bushing parts:
1 Condenser body
2 Electrodes
3 HV connection
4 Head
5 Electrostatic shield
6 Central tube
7 Upper envelope
8 Lower envelope
9 Flange
10 Flange extension
11 Test tap
12 Gaskets
13 Nameplate
14 Oil gauge
15 Binding material
16 Insulating oil
17 Oil expansion part

Figure 2.1.1: OIP bushing description

In OIP bushings, the space between the condenser body and the upper envelope is filled with oil, and in RBP bushings, it is filled with insulating (often highly viscous) liquid. In RIP bushings, this space is filled with oil or, most recently with insulating foam yielding a completely dry construction. The space does not exist if silicone sheds are applied directly onto the condenser body.

RBP, RIP and RIS bushings can withstand operating temperatures up to 120 °C, whereas OIP bushings are resistant up to 105 °C. To reach higher withstand temperature of RIP bushings, paper may be replaced with synthetic material or glass (RIS), but condenser bushings rated for temperatures higher than 120 °C are unfortunately still not available on the market. Recently developed transformers with higher temperature classes of solid and liquid insulation may have top “oil” temperature limits significantly higher than 120 °C, [2.1.3], so it is recommended that bushings for service voltage ≥72,5 kV for higher temperature should be developed in near future.

The basic properties of these bushing types are presented in table 2.1.1, [2.1.4, 2.1.5, 2.1.6].

Table 2.1.1: Basic properties of bushings

	Bushing types		
	RBP	OIP	RIP and RIS
Design description			
Upper (air) envelope	Porcelain	Porcelain or composite	Composite, (porcelain, silicone)
Intermediate filler	Oil or viscous liquid	Oil	Oil, dry foam or none
Lower (oil) envelope	None (RBP body)	Resin, porcelain	None (RIP or RIS body)
Basic properties			
PD, pC	≤ 100/250	≤ 5/10	≤ 5/10
PD regeneration	PD always exist	Yes	No
tan δ, ×10^{-2} or %	Approx. 0,5	Approx. 0,3	Approx. 0,4
Capacitance behaviour	Increasing (oil penetration)	Stable (good condition)	Stable (good condition)
Temperature limits	120 °C (Class E)	105 °C (Class A)	120 °C (Class E)
Overloading behaviour	Well known	Well known	Resin decuring problem
Oil leaks	Yes (oil filled)	Yes	Yes (oil filled)
Resistance to outer flashover	Porcelain rupture	Porcelain rupture	No rupture
Collapse after internal breakdown	Rarely collapse	Often collapse	No collapse
Debris in transformer after internal breakdown	Yes	Yes	Yes (small amount)
Storage problems	Humidity absorption, cracking problems	De-impregnation	Humidity absorption (RIP)
Transformer fire resistance	Medium	Poor to Medium	Good
Earthquake resistance	Medium to Good	Poor to medium	Good
Resistance to vandalism	Medium	Poor	Good
Service with broken upper envelope	Yes (limited time, dry version)	No	Yes (limited time, dry version)

OIP and RIP bushings have a very low partial discharge (PD), typically a few pC at test voltages. RIP bushings are sensitive to the presence of PD because they have no possibility of regeneration, unlike OIP bushings. Regarding PD, RBP bushings have much poorer characteristics. Their PD reaches several hundred pC at test voltages and it can even be one hundred at operating voltage. The reason is that their condenser body always contain some air, so this technology is today considered obsolete. It should be noted that new RBP bushings are not suggested to be exposed to vacuum (with exception of bushings already have been in service, see chapter 6).

Capacitance and tanδ (PF) for OIP and RIP bushings are permanent parameters until a disturbance occurs, making them very favourable for condition diagnostics. RBP bushings gradually increase capacitance during operation (even by ten or more %) and slightly tanδ due to oil penetration in the condenser body and this can mask their defects. This effect may also increase PD activity of the bushing because of disturbed elementary capacitances (oil penetration intensity differs over elementary condensers, see chapter 4.1.4).

2.1.1. Zig-zag OIP technology

It should be noted that behind OIP bushing technology described above (which is today OIP predominant, Figure 2.1.1.1), exist the so-called zig-zag OIP technology (herringbone pattern, fishbone pattern or lined ink OIP technology). The zig-zag condenser body in does not have classical electrodes. The electrodes are zig-zag conductive lines continuously painted on the paper. This paper together with not painted paper, is wrapped on the central tube or conductor to form the condenser body as shown in Figure 2.1.1.2. This condenser body has a huge number of elementary condensers, so when disturbances occur, bushing may gradually change their capacitance.

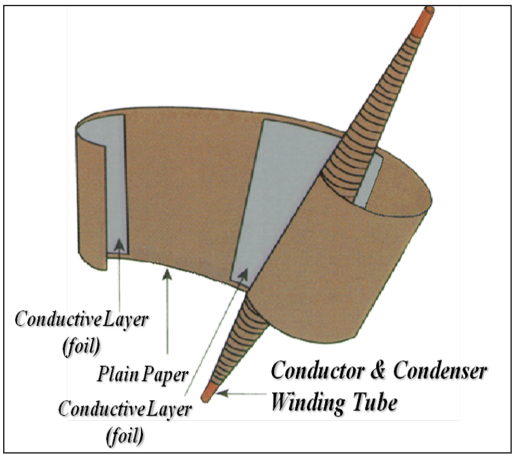


Figure2.1.1.1: Inserted conductive foil OIP

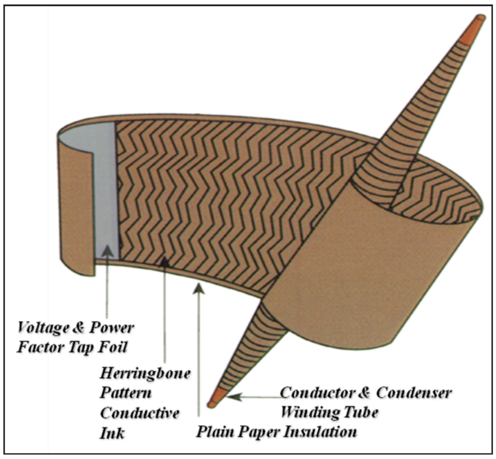


Figure 2.1.1.2: Zig-zag condenser OIP

These bushings were manufactured from 1954 until 1986, for bushings ranging from 15 kV to 230 kV voltage classes in the United States of America. Tens of thousands were put into service during this period and many are still in service today. These Type U bushings were designed with a condenser core made from oil impregnated kraft paper insulation inside an oil-filled shell. The shell consists of a top cap, an upper insulator (porcelain), a metal mounting flange, a lower insulator (porcelain) and a lower support/terminal. For sealing purposes, all parts are held together through the use of a centrally clamped conductor and/or spring assembly method.

The principal behind the use of a condenser in bushing design is to create equal capacitance layers thus providing equal voltage steps, resulting in a uniform voltage gradient across or throughout the bushing shell and internal insulation. The zig-zag pattern was implemented by printing conductive ink (Rescon Ink) on the surface of the paper in a zig-zag pattern as shown in Figure 2.1.1.2, to form the capacitive prints. Use of the small equally spaced prints in each bushing allowed thousands of capacitive layers for excellent grading of the voltage, thus producing a very uniform voltage distribution. To allow for sufficient insulation between layers, the winding consisted of two pieces of kraft paper wound into the condenser, the ink lined paper (with the thousands of prints) and a blank piece of kraft paper insulation. The layer with the ink lines was necessarily shorter than the other, as shown in Figure 2.1.1.2, to separate the layers dielectrically.

2.2. Resin impregnated synthetic bushings

The Resin-Impregnated Synthetics (RIS according to [2.1], but other abbreviations are used too), technologies of dry high-voltage capacitance-graded bushings have been developed in recent years by different manufacturers. RIS transformer bushings are being manufactured today for voltages up to and including 330 kV and service experience is being collected, [2.2.1, 2.2.2]. When compared to OIP and RIP bushings, in RIS technology paper is replaced by synthetic fibre fabric, Figure 2.2.1. The condenser core is wound from this fabric with inserted field-grading foils and the assembly is impregnated with inorganic-filled epoxy resin. After hardening, the outdoor part of the bushings may be directly over-coated with silicone sheds. Most of the differences of RIS with respect to the traditional technologies comes from the elimination of the cellulose from the insulation material and from application of the inorganic particle-filled resin, and because of this humidity absorption is practically eliminated. The lack of paper in the material means there is no need to dry the core prior to impregnation with resin, and very good storage properties, independent of the storage environment. As a result, the dielectric loss factor of the bushing does not depend on the storage conditions [2.2.1].

Figure 2.2.1: RIS and OIP bushing unimpregnated condenser body (left), RIS high hydrophobicity (right)

The low processing shrinkage and relatively small amount of exothermic energy released during the hardening process of the filled resins allows for casting large bulk components in the fast injection and gelling process. Moulding directly to the final shape of the component is possible without the need of further machining. A silicone external insulator suitable for the outdoor conditions, can be directly moulded over the air-portion of the condenser core.

2.3. HVDC bushings

HVDC bushings are installed on the valve side of a converter transformer. According to [2.3.1], these bushings are exposed to large AC voltage superimposed on large DC voltage, and AC load current rich with harmonic content compared to normal power transformers.

HVDC bushings are designed in RIP as well as in OIP technology. The active part of the bushings on the air side can be protected by a composite insulator, porcelain housing or in some RIP indoor applications it can be without any housing. In that last case, the creepage is improved by a wave structure of the resin condenser. The space between condenser core and air side housing can be filled with SF_6 gas, a special kind of foam or oil. In general, the bushings have a conical geometry on the oil side. RIP bushings get this geometry directly by turning the RIP material in production. OIP Bushings have an additional housing made of porcelain or cast resin above the condenser core. Other designs plug in the graded OIP condenser directly into the bushing end shield barrier system under oil. Generally, interchangeability between RIP and OIP bushings is not allowed because of the different conductivity of the dielectric materials used. If they are interchanged, the effect of the electrical field should be additionally checked. The dielectric design of HVDC bushings needs to take into consideration that the electrical field distribution under DC voltage is different from AC voltage. Under AC voltage the electrical field distribution is determined by the permitivity of the different materials used. Under DC voltage the electrical field distribution is determined by the conductivity of the materials used, and these may change markedly with temperature. Additional requirements, such as the polarity reversal processes (or transient processes) affect the electrical field distribution in a way completely different from DC or AC electrical field distribution. Immediately after the voltage transition, the AC electrical field distribution is dominant, but as time passes, the electrical field changes (according to the insulation time constant) to a DC distribution. After the next transition, the AC electrical field is superimposed onto the existing DC electric field distribution which can cause severe stress in insulation. For AC or DC electrical field analysis, a so called static electrical field solver is used. For polarity reversal, a dynamic electrical field solver should be used.

The conductivity of the insulation materials is much more subjected to change with temperature, impurities and ageing [2.3.2] (up to three orders of magnitude or so in regular temperature range) when compared to permitivity (approx. up to 10 % or so in regular temperature range). This problem is still not completely solved and because of that a CIGRE JWG A2/D1.41: HVDC transformer insulation: oil conductivity, is formed to help in this issue, [2.3.3]. All of this means, that the design process of the HVDC insulation system is much more complicated in comparison to AC insulation systems.

HVDC bushing voltage tests are normally performed with the same barrier system around their transformer end of the bushing and end shield placed in the turret as will be used in transformer. The barrier system can be very complicated – consisting of several pressboard cylinders of different diameters and heights and specially shaped paper boards. The barrier system is designed in conjunction with the bushing's condenser body and thus is usually designed by or in co-operation with the bushing manufacturer. This has a major impact on the cost of an HVDC bushing because each bushing type is a custom designed unit. In comparison, such requirements do not exist for ordinary AC bushings where the size of the testing tank filled with oil is not limited. This fact may cause some problems in the case when the bushing end screen is covered with thick layer of epoxy resin, refer to section 4.1.3.

3. Bushing failure rate

Generally, bushing failure occurs when the service stress exceeds the withstand strength of a certain material. From a certain point of view, the strength can be exceeded generally or locally. In the first case, there is a complete loss of bushing service characteristics which is represented by a bushing failure, and in the second, there is an initial fault that can develop into a failure over service time. A transformer may have up to 10 bushings (in some cases even more) and the failure of any bushing has the consequence of a transformer failure. A bushing explosion (burst) damages a transformer in many different ways. An upper porcelain envelope burst launches fragments at enormous speeds which possess a destructive power even at a distance of up to one hundred meters. The burst of the bushing's lower part damages a transformer in such a way that the conductive and burned debris of the condenser body and lower envelope (if it exists) pollutes the transformer's active part, Figure 3.1, [3.1], (condenser electrodes are usually made of a very thin aluminium foil or by painting conductive ink on the paper). Debris can easily be carried by the transformer's flowing oil relatively far from the failure location. Cleaning of the transformer's active part from bushing fragments is a very sensitive and difficult job with no guaranteed of success. There is always a possibility that some conductive particles remain in the insulation system which can cause a subsequent failure (insulation breakdown) or PD.

Figure 3.1: 400 kV failed bushing (up, left) and fire at 300 MVA transformer (right); bushing fragments in transformer turret and tank (down, left)

It should be noted that the price of a single bushing is just a fraction of transformer price. According to [2.1.4], for ordinary AC transformers, the price of the highest voltage bushing is approximately in the range of 0,4 to 0,8 % of the transformer price.

From the above and the huge development in bushing condition diagnostics over the last several decades, bushing failure can be divided into two typical scenarios:

- **Incipient bushing failure** – no serious consequence for the transformer (except few days loss of availability for bushing replacement).
- **Terminal bushing failure** – usually represented by a bushing explosion (burst, collapse, violent rupture) with major transformer failure as a consequence. It should be noted that the term "terminal" used in this failure definition is not related to the point where a bushing is connected.

Costs of a terminal bushing failure are tremendously higher than for an incipient bushing failure. The goal of bushing condition monitoring (periodic or off-line, and continuous or on-line) is to recognize as many faults as possible at their earliest (incipient) stage and, in that way, reduce the number of terminal bushing failures.

It is important to note that, looking at the total number of terminal and incipient bushing failures, they cannot be prevented by diagnostic monitoring. They are determined by bushing quality and service conditions. However, with application of diagnostic monitoring together with maintenance, the number of terminal bushing failures is decreased, service reliability is increased, and economic benefits are significant. Without diagnostic monitoring and maintenance, all incipient bushing failures (sooner or later) develop into terminal ones, such as, bushing collapse, rupture or explosion with huge consequences for the transformer, the power system and the environment.

3.1. Survey objective

It is fairly obvious that bushings significantly affect service reliability and availability of a transformer, however bushings failures are rarely analysed separately from transformer failures. This means that, because of the consequence, only terminal bushing failures are analysed. This survey is an attempt:

- to expand bushing failure research from only terminal bushing failures to incipient bushing failures detected with certain diagnostic methods or condition monitoring,
- to research bushing failures during transformer factory acceptance testing and how bushings standards influence these bushing failures,
- to collect bushing in-service failure data from bushing manufacturers, and
- to collect data about actual bushing diagnostic practices (periodic or off-line and continuous or on-line) performed by transformer users.

These objectives lead to the four questionnaires, referred to in section 3.3.

3.2. Existing bushing failure data

According to the data from various international researches and electric power utilities, bushings cause 5 to 50 %, of transformer failures [1.1]. According to [2.1.1] bushing failures are the most common cause of transformer fires and can cause huge collateral damage in the switchyard, (Figure 3.1). [1.2] indicates that 30 % of generator step-up transformer failures are caused by a bushing malfunction. Bushing failures also cause 56 % of failures accompanied by fire. According to the analyses in which individual components are ranked by the number of transformer failures they are causing, bushings are ranked as one of the first three items.

It should be noted that failure rate depends on failure definition. For example, if only transformer failures with outages longer than a week are recorded (as in [3.2.2]), more than a half of the transformer failures caused by bushings will not be recorded in the survey, (Figure 3.4.1.4). Different failure definitions could be the cause of the high statistical spread of bushing-related transformer failures found in various references, [4.1.3.2]. Also, discussions between WG members and other experts revealed that, in some utilities, bushings that are replaced because of poor diagnostic results (i.e. a bushing in poor condition which means incipient failure) but are not recorded, and thus are not included in surveys. In that sense the bushing is simply considered as a spare/replaceable part of the transformer undergoing maintenance.

SC 12 data

SC 12 – Transformers, initiated WG 05 to deal with transformer failures. The survey started in 1978 on a population of transformers $U_m \geq 72$ kV, not older than 20 years. Based on a population of more than 47000 transformer-years, in the period of 1968-1978, more than 1000 failures have been recorded, and carefully analysed [3.2.1]. The transformer parts or components initially causing the failures was presented separately for GSU transformers, network transformers and autotransformers. Their abundances for the whole population are presented in Table 3.2.1. Bushings (originally French: traversees) are ranked in third place with abundance of 15,6 %, after tap changers and windings, and before tank and dielectric fluid and other accessories.

WG A2.37 data

The first comprehensive international transformer failure survey after CIGRE SC 12 WG 05 was performed by CIGRE WG A2.37, [3.2.2]. The working group has collected 964 major failures (failures that have for the consequence at least 7 days long outage) on a population of 167.459 transformer-years. Failures occurred from 1996 to 2010. The obtained failure rate of all transformer groups (except GSU 300 to 500 kV) was below 1 %.

Table 3.2.1: Transformer parts failure abundance according to [3.2.1]

Transformer parts	Failure abundance, %
Tap changers	30,1
Windings	23
Terminals (bushings)	15,6
Tank and dielectric fluid	13,6
Other accessories	14,4
Magnetic circuit	3,3

Regarding bushings, some interesting facts can be extracted:

- Bushings caused 14,4 % transformer failures, over all observed voltage ranges.
- Bushings similarly affect failures of substation and GSU transformers. For voltage ranges ≥ 100 kV bushings caused 17,2 % failures of substation and 14,2 of GSU transformers.
- Bushings are ranked in the third place between transformer parts, after windings (47,4 %) and tap changers (23,2 %) and before lead exit (6,3 %) and core and magnetic circuit (3,8 %).
- Bushings related failures rise with voltage except for the voltage ≥ 700 kV. Bushing related failures for various voltage ranges are: 69-100 kV: 0 %; 100-200 kV: 13 %; 200-300 kV: 16,6 %; 300-500 kV: 21,9 %; 500-700 kV: 28,7 %; ≥ 700 kV: 9,1 %.
- Bushings similarly affect failures of older and newer transformers. For transformers produced before 1980, bushings caused 15,9 % of failures and for transformers produced after 1980, bushings caused 18,1 % of failures.
- Bushings caused 37,8 % of transformer failures with fire and/or explosion as a consequence (30,6 % HV, 5,6 % MV and 1,6 % LV bushings).
- 47 % of bushing failures have a consequence: fire (30,4 %), explosion (10,4 %), leakages (5,2 %) and collateral damages (0,9 %).

It can be summarised: WG A2.37 research [3.2.2] confirms the earlier CIGRE data, [3.2.1], that bushings significantly affect transformers reliability. Bushing failures often lead to severe consequences for transformers such as fire, explosion, leakage and collateral damage.

IEEE Canadian and American experience

Sometime before 2006, a survey was conducted among Canadian and American utilities, [3.2.3], to undertake a review of available diagnostic techniques for bushings, and most importantly the experience of utilities with these techniques. The survey was also motivated by the fact that bushing failures causes about 35 % of transformer failures with forced outages, [3.2.4, 3.2.5].

Fifteen utilities responded to the questionnaire that consists of only 8 questions (some of them with sub questions). The bushing population covered is about 67000 bushings, of which about 94 % of them were OIP bushings. One question concerned bushing failure experience and 7 utilities responded to this question. Only forced outages were taken into account over the past approximately 30 years: 234 of them were violent and 327 were classified as other failures. So, about 45 % of bushing failures with forced outage were violent/catastrophic in nature with a potential danger to utility staff, equipment in the vicinity and the environment.

The predominant bushing failure causes for utilities are design, manufacturing, lightning or other external effects, PD in bushing insulation, contamination/moisture ingress of oil and thermal problems. About a third of utilities answered that bushing failures are generic in nature (one particular manufacturer, construction type or age).

Regarding diagnostic methods, the most popular off-line (periodic) method is power factor (PF) testing in 4 to 10 year intervals. No utilities used diagnostic methods based on bushing insulation polarisation spectrum (PDC, RVM, FDS, see section 5.2.3). Between periodic, in-service methods the most popular are visual inspection (performed monthly) and infra-red (IR) scanning (performed yearly). Three out of fifteen utilities do not perform any off-line tests and only one utility did not perform periodic in-service tests on bushings. The most effective diagnostic methods are PF, visual inspection and IR scanning. With regard to diagnostic method effectiveness on the prevention of a bushing failure, no specific numbers of replaced bushings because of poor condition are listed.

Australia – New Zealand experience

During 2005, a survey questionnaire was developed by an Australian utility to seek information on network asset management practices for 110-132 kV condenser style transformer bushings within Australia and New Zealand, [3.2.6]. The intention of the survey was to identify current industry replacement practices for bushings in service, and collect information on diagnostic testing parameters. A summary of the survey findings is presented below. The survey was answered by 8 different participants and covers 3841 bushings from 33 different manufacturers. The two main types of bushings included in the survey were RBP with porcelain sheds – approximately 1050 bushings with an average age of more than 30 years, and OIP with porcelain sheds – approximately 1000 bushings typically less than 10 years old. Of the bushings in the survey 30 % were less than 10 years old, and 45 % more than 40 years old.

Off-line diagnostic testing is done by all survey participants in the form of dielectric dissipation factor (DDF, tanδ). Most participants test at a 4-yearly interval. No participants use X-ray analysis, Recovery Voltage Measurement, Polarisation/Depolarisation current or Frequency Domain Spectroscopy procedures. The most common periodic testing on energized transformers includes infra-red thermography and oil gauge readings. On-line (continuous) DDF monitoring is used by 3 participants. 63 % of survey participants recorded that DDF test results were affected by external contamination (i.e. coal dust) or high humidity. All survey participants would replace rather than refurbish their suspect bushings. The most common basis for bushing replacement was on DDF test results.

40 bushing failures were reported, and the average age of these failed bushings was 30 years. 6 (15 %) of the failures were terminal (catastrophic) and 34 (85 %) of the failures were incipient (bushings found to have poor test results and they were subsequently replaced). The cumulative age distribution of the failed bushings is on Figure 3.2.1, and shows a rapid increase in the range of bushings aged 25 to 30 years.

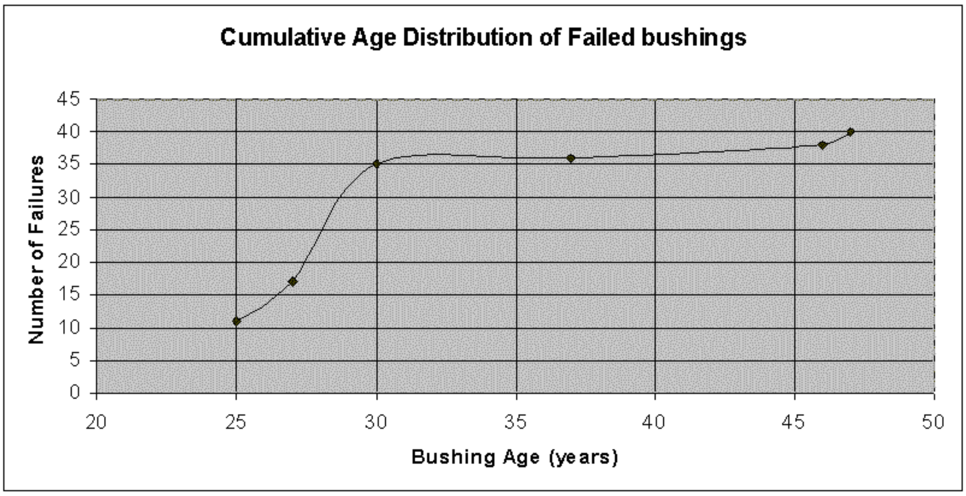


Figure 3.2.1: Australia – New Zealand cumulative age distribution of failed bushings

Croatian experience

Power transformer failure analysis performed at the Croatian transmission network operator [3.2.7], over a 15-year period and a relatively small population of 2603 transformer-years showed that bushings were the most common cause of transformer failures, at 31 %. Transformer off-line (periodic) testing was based on approximately 5 years interval and includes C_1 and $\tan\delta_1$ measurements on condenser type 123 to 420 kV bushings. In this survey, transformer failure definition was that both, incipient and terminal bushing failures were recognized as a transformer failure. The distribution of bushing failures was approximately 2/3 incipient and 1/3 terminal bushing failures. That means if we extract bushing incipient failure, bushing terminal failure was the cause of only about 13 % of transformer failures. This clearly shows that failure definition can have huge impact on failure survey results.

ASEAN data

A comprehensive transformer and bushing failure study was performed by South East Asia Maintenance Committee [3.2.8], the Joint Maintenance Corporation among 3 major ASEAN transmission utilities comprising of TNB Malaysia, PLN Indonesia and EGAT Thailand. They take up to approximately 60 % of the energy demand of the ASEAN region and have installed 3367 transformers with a total power of 293 GVA. Unfortunately, the quantity of the different bushing types (RBP, OIP, RIP) in-service aren't listed. The reference period was 2001 to 2014. The transformer failure definition was described as a loss of service ability caused by major components of the transformer which required major repair or replacement of the components or transformer. Transformer failure causes found are: winding 42,4 %, OLTC 31,2 %, bushing 23,4 % and cable box 3 %. About 75 % of the bushing failures resulted in transformer fire. Bushings are definitely ranked first as the cause of transformer fire. The estimated age of failed bushings is approximately 15 years. Bushing failure root cause is shown on Figure 3.2.2.

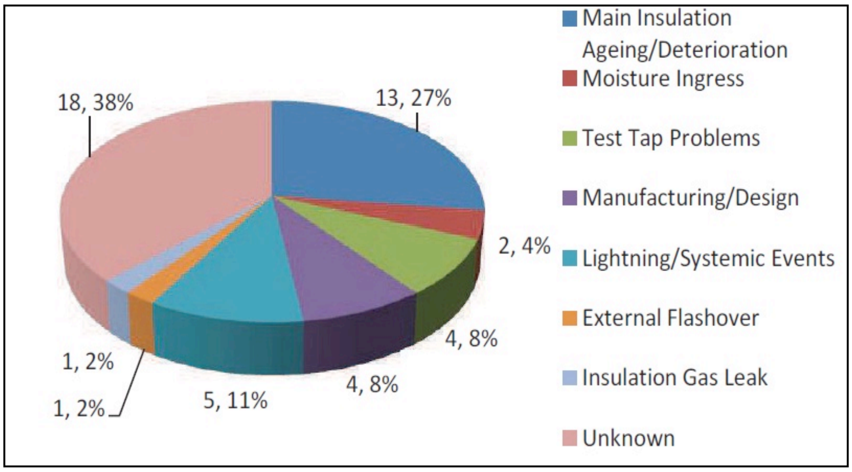


Figure 3.2.2: ASEAN, [3.2.8] bushing failure root cause

Ignoring the Unknown causes, the first ranked bushing failure root cause is main insulation ageing or deterioration. The second is lighting or systemic events (it is a bit unusual to put these two root causes together). Capacitance and PF limits are defined at commissioning, for the warranty period and in service after warranty. IR temperature limits are defined for the warranty period and in service after warranty. Several failure cases/modes are analysed: draw lead bushing fast transient issue, monkey damage to the upper envelope polymeric sheds (an important but still unresolved problem), condenser core damage and test tap problems.

Oil sampling is not recommended as a routine practice or on a regular basis. The Corporation stated: ”All utility members do not recommend oil sampling on hermetically sealed bushings due to high humidity environment unless the task is urgent and performed under supervision of relevant skilful personnel… However, the practice of oil replacement or topping-up SHAL NOT BE CARRIED AT SITE. There are histories of catastrophic high voltage bushing failures reported by members after such maintenance tasks”.

Based on the experience several mitigation measures are listed: RIP type of bushing should be preferred for the future projects and during the procurement process additional specifications are recommended. Certain bushing maintenance and storage practices are also recommended. Bushing on-line monitoring systems are recommended in sensitive cases.

3.3. Bushing failure definitions

The following bushing failure definitions were agreed upon during the early stages of the working group. The definitions were an important part of the bushing reliability questionnaires to ensure all contributors were following the same guidelines.

Incipient bushing failure is a bushing's partial lack of performance which could develop into a terminal bushing failure. It is recognised either by visual inspection (surface cracks, oil leaks) or by another diagnostic method and it can be prevented by bushing replacement or repair, usually with no consequences for the transformer and in a relatively short period of time (i.e. ≤ 7 days). Their causes are essentially the same as for terminal bushing failures with only one difference – they are in the initial stage. In most cases, incipient bushing failure results in a minor transformer failure.

Terminal bushing failure is an instantaneous loss of the bushing’s service ability. It is usually a bushing "rupture" or "collapse" (explosion/burst) that often causes huge damage to the transformer. It is often accompanied by fire and high collateral damage. The cause of the rupture is always a breakdown either of the condenser body, or the upper or lower envelope. The causes of those breakdowns vary, from imperfections in the bushing insulation system, improper connection to the switchyard, moisture penetration, to overheating caused by poor or improper contact, etc. In most cases, terminal bushing failure results in a major transformer failure.

Transformer acceptance test (TAT) bushing failure occurs if a new transformer fails the acceptance test at the factory or at site because of the bushing. The bushing should be replaced or repaired before the next transformer acceptance test.

Note:

Transformer **A**cceptance **T**est (TAT) is more commonly known as (transformer) **F**actory **A**cceptance **T**est (FAT). It was decided to use TAT because FAT may imply the bushing factory’s acceptance testing which is not part of our research.

Bushing failure with forced outage: In typical cases, it is a trip activated by the transformer protection (or manually tripped, due to an alarm, within 30 minutes). Forced outage is often related to bushing terminal failure [3.2.1].

Bushing failure with scheduled outage: In typical cases, it is a transformer taken out of service by staff in a planned manner i.e. more than 30 minutes from the first noticeable effect. Scheduled outage is often related to bushing incipient failure, [3.2.1].

3.3.1. Bushing failure survey questionnaires description

Four questionnaires were developed and conducted:

- **Questionnaire Q1: Bushing in-service failure questionnaire**. This deals with bushing in-service incipient and terminal failures, and is intended for transformer users/utilities. The main goals are obtaining the bushing failure rate and collecting relevant facts about bushing failure for statistical purposes, refer to Annex 1.
- **Questionnaire Q2: Transformer Acceptance Test (TAT) failure questionnaire for bushings**. This deals with bushing failures that appear during transformer acceptance testing (TAT) and it is intended for transformer manufacturers. The main goals are to obtain the TAT bushing failure rate and collecting TAT bushing failure relevant facts for statistical purposes, refer to Annex 2.
- **Questionnaire Q3: Bushing manufacturer failure data questionnaire**. This deals with bushing in-service failures, using data from bushing manufacturer's records. It is intended for bushing manufacturers. The main goal is to obtain the bushing failure rate from bushing manufacturer's quality records data. It should be noted that this questionnaire dealt only with bushing failure data reported to the bushing manufacturer. In most cases, only forced outages are reported to the bushing manufacturer, which means most of these bushing failures will be terminal, refer to Annex 3.
- **Questionnaire Q4: Bushing diagnostics, maintenance and failure practice questionnaire**. This deals with bushing diagnostic practices and it is intended for transformer users/utilities. The main goals are collecting relevant facts about the utility's/user's bushing diagnostics practices (periodic and continuous), bushing maintenance and failure records practice, refer to Annex 4.

The reason for the splitting survey into four parts (four questionnaires) is simplify the completion of the questionnaires. In this case, simplicity is crucial because bushing failure data (especially for incipient failure) is expected to be difficult to find. Complicating the matter is that the staff completing the questionnaires have far more knowledge about transformers than they do about bushings, where bushings are just a component of the major asset.

Drop-down lists are extensively used. They offer typical answers and help to make survey analysis easier and more accurate.

The survey was organized through WG A2.43 members and their colleagues with the help and support of A2 members. All row (unconsolidated) data was kept confidential, only accessible to the person who completed the questionnaire and the WG convenor.

3.4. Results of the survey

The survey started in April 2013 and lasted up to the end of 2014. The WG collected data from 32 utilities, 10 transformer manufacturers and 7 bushing manufacturers. For all four questionnaires, 70 responses were received from 22 countries: Australia, Austria, Bosnia and Herzegovina, Brazil, Canada, China, Croatia, Czech Republic, France, Germany, Hungary, Indonesia, Italy, Japan, Montenegro, Netherlands, New Zealand, Portugal, South Africa, Spain, Switzerland and United States of America. Responses to particular questionnaires are as follows:

- Q1: 25 responses from 25 utilities (15 countries)
- Q2: 9 responses from 10 transformer manufacturers (8 countries)
- Q3: 5 responses from 7 bushing manufacturers (5 countries)
- Q4: 31 responses from 31 utilities (16 countries)

3.4.1. Q1 data and analysis

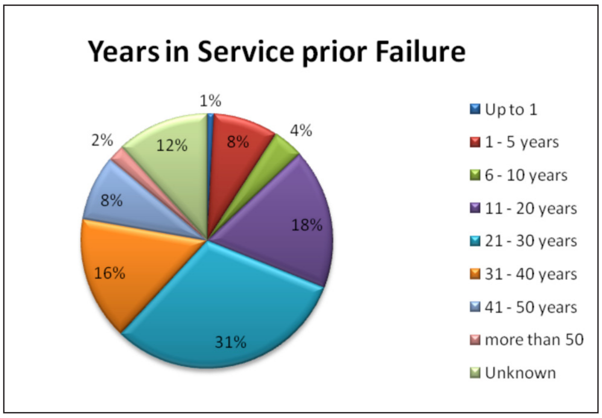
Q1 deals with bushing in-service incipient and terminal failures.

Summary of Q1 data - 240 failures were collected on more than 101.000 of in-service bushings, 73 terminal and 160 incipient. Terminal failures make up about 30 % of all reported failures. This is similar to the Croatian survey, where terminal failures made up about 1/3 of reported failures. The Australia and New Zealand survey was somewhat different, with fewer actual failures – about 15 % of total failures. The data from our survey and references revealed that the number of incipient failures is approximately 2 to 5 times greater than the number of terminal failures. Results clearly reveal that bushing diagnostics, periodic and continuous, helps in the prevention of terminal failures. The reference period was from 5 to 12 years in the time frame 2000 to 2013. The year of manufacture of the bushings ranged from 1950 to 2012.

The main problem with Q1 is poor data about bushing population. In many cases, the reference period for the bushing population count did not match the reference period for failure count. It was assumed during the work on the questionnaires that bushing population would be one of the major problems. To overcome this, a method of bushing population calculation was suggested for utilities that do not have their own bushing population data, see Annex 1. Despite this, the results from the bushing population data was quite poor and thus calculation of the bushing failure rate could not be completed in an accurate way. However, Q1 revealed a lot of interesting data related to bushing in-service reliability.

Identification of the failed bushings

Almost all failed bushings in Q1 are AC bushings – 98 %. Only 2 % are HVDC bushings. As expected, 86 % are oil-air bushings followed by 3 % oil-oil and 2 % oil-SF_6 bushings (9 % are characterized as “unknown“ in this question). According to the bushing connection type 63 % were referred to as draw lead followed by 7 % bottom connected and 6 % draw rod (24 % are characterized as unknown in this question). The years of service prior to failure is shown in Figure 3.4.1.1.



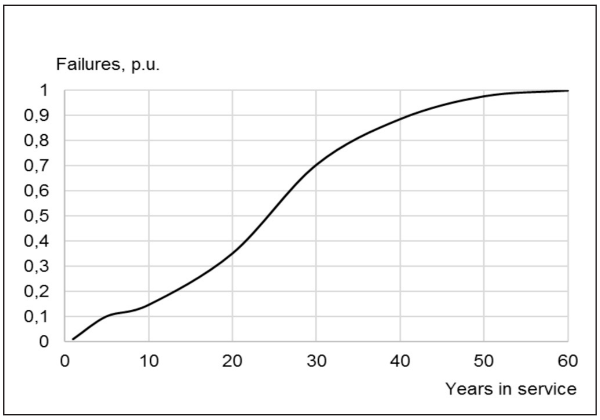
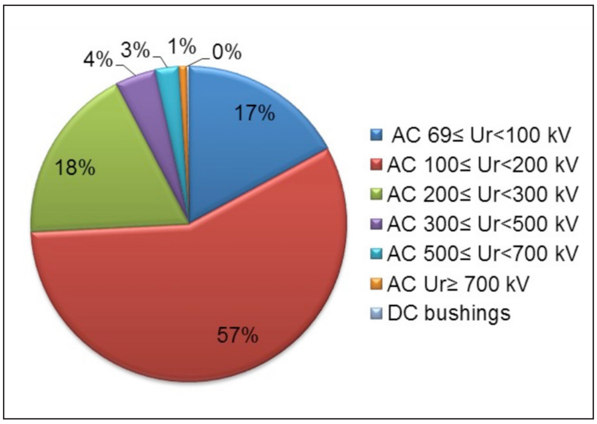


Figure 3.4.1.1 Years in service prior to bushing failure (distribution – left, cumulative – right)

Abundance according to the rated voltage of failed bushings and in the bushing population is shown in Figure 3.4.1.2.



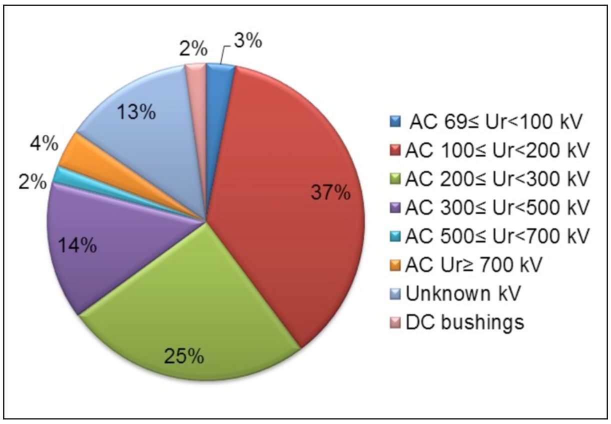


Figure 3.4.1.2: Bushing population rated voltage (left) and failed bushing rated voltage (right)

It can be noticed that (with some exceptions) the ratio between the failed bushing relative abundance (Figure 3.3.1.2 right) and the relative bushing population for a certain voltage (Figure 3.3.1.2 left) rises with rated voltage. This suggests that the bushing failure rate increases with rated voltage.

The influence of the insulation system type can be seen from Figure 3.4.1.3.

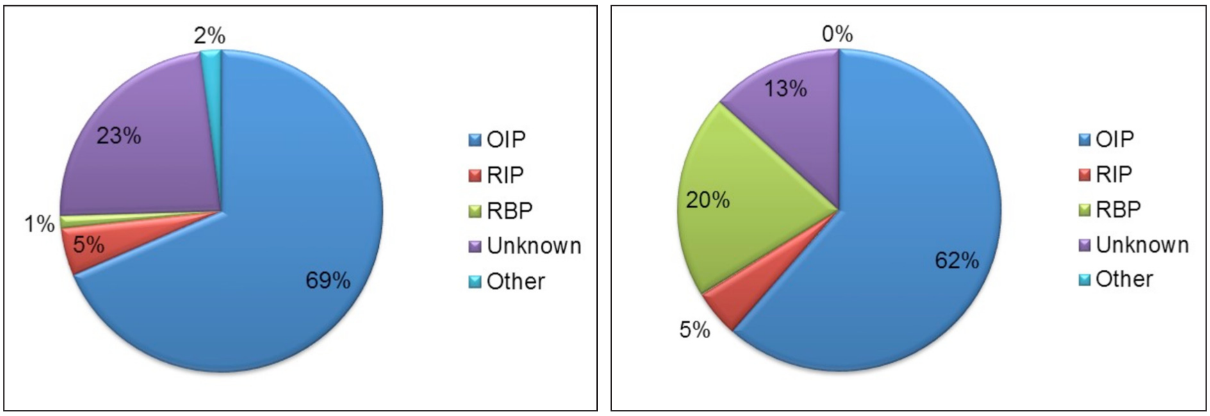


Figure 3.4.1.3: Bushing population (left) and failed bushing insulation system type (right)

It is interesting that the relative abundance of OIP and RIP insulation systems in the bushing population and in the failed bushing population are almost same in spite of the fact that OIP bushings are probably older overall than RIP bushings. To the contrary RBP bushings revealed a much greater abundance of failed bushings than in the bushing population. This means RBP bushings have a much higher failure rate than OIP and RIP. A reason for this is definitely the age of the RBP bushings – many are now at the end of their lives. Whilst it at first seems that RBP bushings have a failure rate approximately 20 times higher than other types, this is probably not the case as a high proportion of the bushings with an “unknown” insulation system are likely RBP. This is because RBP bushings are frequently the oldest and thus the most difficult to identify.

Identification of outages

The total amount of bushing failures collected breaks down to 67 % incipient, 30 % terminal and 3 % unknown, while the outage types are 74 % scheduled and 26 % forced. Bushing incipient failures practically results in only scheduled outages (98 %). To the contrary, bushing terminal failures results in 73 % of forced outages. Of course, a forced outage is much costlier and more dangerous to the system. Outage duration based on all collected bushing failures is sown in Figure 3.4.1.4. More than a half of all bushing failures result in transformer outages up to a week.

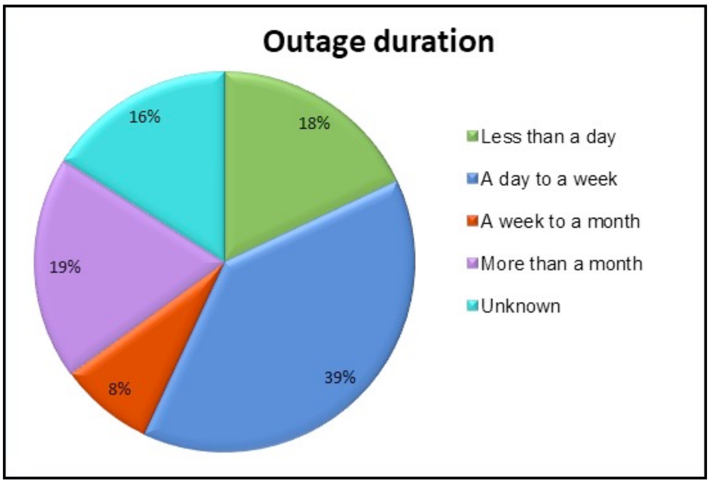


Figure 3.4.1.4: Transformer outage duration based on all collected bushing failures

Bushing failures divided into terminal and incipient are shown in Figure 3.4.1.5

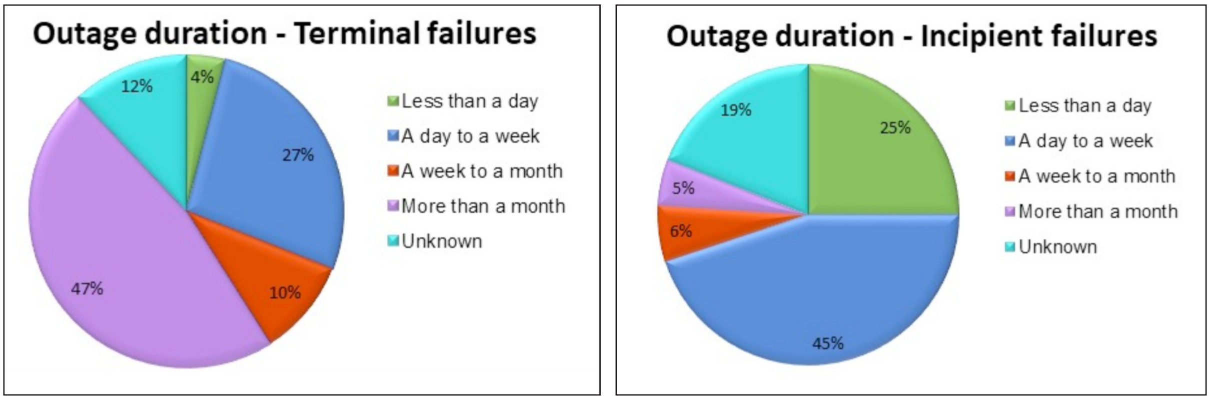


Figure 3.4.1.5: Transformer outage duration caused by bushing terminal failures outage (left) and bushing incipient failure outage (right)

As shown in Figure 3.4.1.5, a transformer outage caused by a bushing incipient failure is of a much shorter duration than that caused by a terminal failure. 70 % of incipient bushing failures result in a transformer outage duration less than a week and only 5 % are more than a month. Bushing terminal failures have results in a transformer outage duration of less than a week in 31 % of cases and more than a month in 47 %. The main reason for this is that terminal bushing failures often cause significant damage to the transformer, which needs to be repaired before the transformer can be returned to service. This makes a strong case for applying on-site bushing diagnostics.

Note

The analysis above was derived with the unknown (or not answered) outage duration included. If we exclude these events, the numbers are a bit more in favour of bushing on-site diagnostics. For bushing incipient failures, 87 % of transformer outages are up to a week and 6 % are more than a month. For bushing terminal failures, 36 % of transformer outages are up to a week and 53 % are more than a month.

Visual appearance of bushing

Based on all bushing failure data collected, visual appearance is shown in Figure 3.4.1.6.

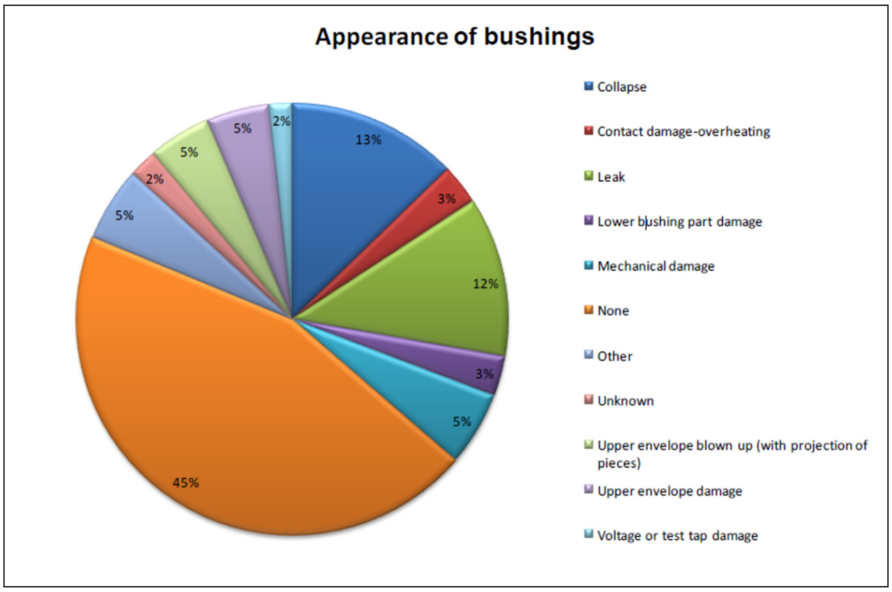


Figure 3.4.1.6: Visual appearance of all failed bushings

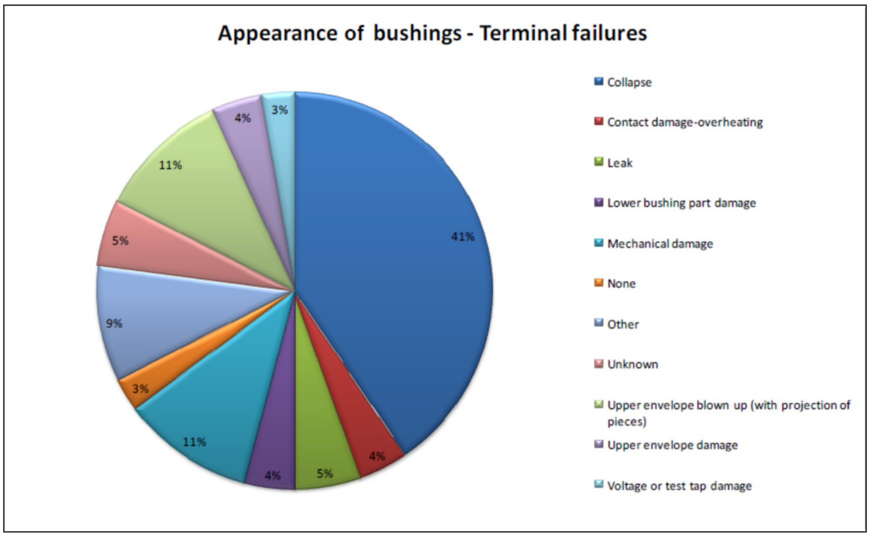


Figure 3.4.1.7: Visual appearance of bushings with terminal failures

The most abundant visual appearance for all failed bushings is "no visual appearance" in a bit less than a half of the cases (45 %) followed by bushing collapse (13 %) and oil leaks (12 %). It should be noted that about 5 % of all bushing failures end with one of the most undesirable events: upper envelope burst (upper envelope blown up with ejection of pieces). It should be noted here that the visual appearance of a failed bushing represents only the most prominent visual effect as a fact. The visual appearance of bushings with terminal failures is shown in Figure 3.4.1.7 and with incipient failures in Figure 3.4.1.8.

The most abundant bushing terminal failure visual appearance is collapse in a bit less than a half cases (41 %) followed by mechanical damage (11 %) and upper envelope burst (upper envelope blown up with ejection of pieces) (11 %). Sum of all mechanical damages (i.e. collapse or upper or lower envelope blown up are only specific and prominent kind of mechanical damages) is 71 %. It is also interesting that the total number of none and unknown visual appearance is only 8 %. Voltage or test tap damage and contact damage – overheating represents in sum only 7 %.

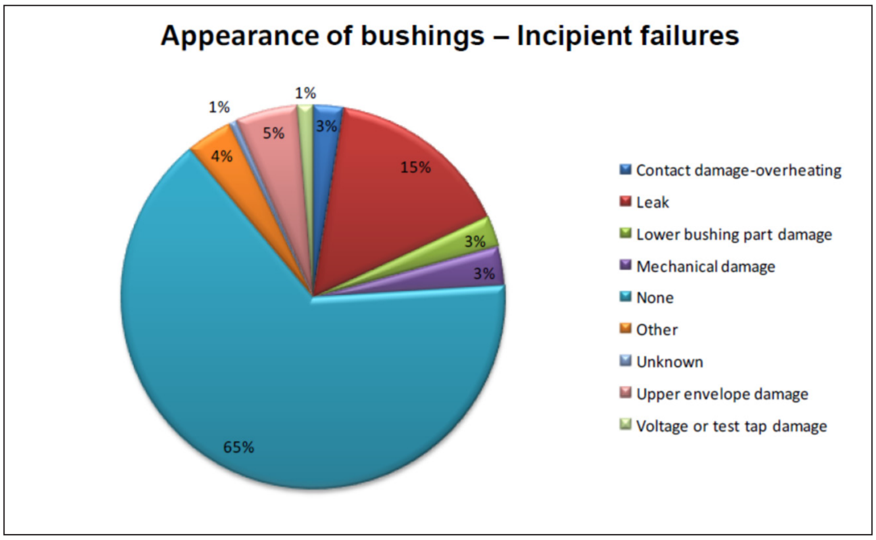
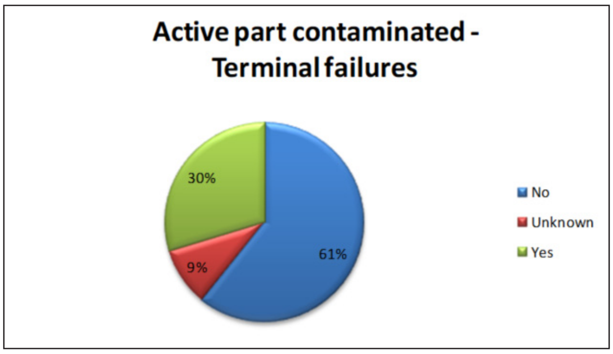


Figure 3.4.1.8: Visual appearance of bushings with incipient failures

The most abundant visual appearance on the bushing after incipient failure is "no visual appearance" in about 2/3 of the cases (65 %), followed by oil leaks (15 %). It is fairly obvious that bushing visual appearance after a terminal failure is much more severe than after an incipient failure. To support this statement, Figure 3.4.1.9 shows the transformer active part contamination after a bushing failure.



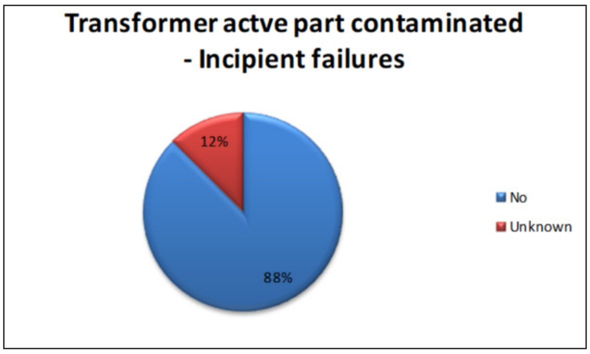


Figure 3.4.1.9: Transformer active part contamination with bushing debris: terminal failures (left) incipient failures (right)

After a bushing terminal failure, in almost one-third of the cases (30 %) the transformer active part is contaminated with bushings debris but in 61 % no active part contamination is recorded and in 9 % the result is "unknown". As a consequence of bushing incipient failure in 88 % of the cases no transformer active part contamination is recorded, and in 12 % of the cases the result is "unknown" and the transformer active part contamination isn't recorded.

Identification of failure causes

Data on failure causes should be treated with some caution, as these were mostly identified by users who may not be experienced and trained in bushing failure investigation. Real bushing failure causes very often are not visible on the first inspection. The investigation of bushing failure causes seems to be worse than, for example, transformer failure causes because power transformers are the main asset in utilities and more educated and experienced personnel are available in this area.

Based on all bushing failures collected, the failure cause is shown in Figure 3.4.1.10. The most abundant is condenser body defect in almost half of the cases (41 %), followed by unknown (17 %) and seismic activity (6 %).

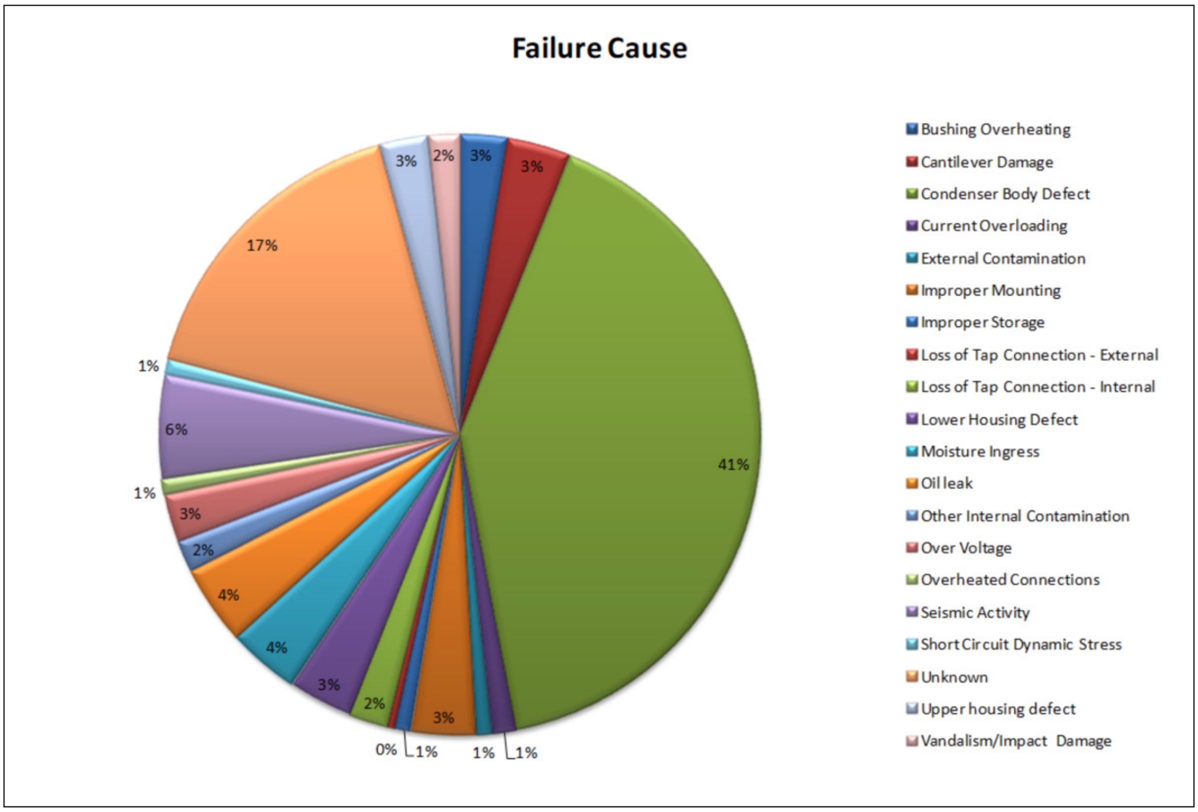


Figure 3.4.1.10: Bushing failure causes based on all bushing failures collected

Regarding bushing terminal failure causes, Figure 3.4.1.11, the most abundant failure with the exception of unknown (19 %), is a bit surprising, seismic activity (18 %), followed by condenser body defect (12 %), moisture ingress (9 %) and overvoltage (7 %). Bushing incipient failure causes are shown in Figure 3.4.1.12.

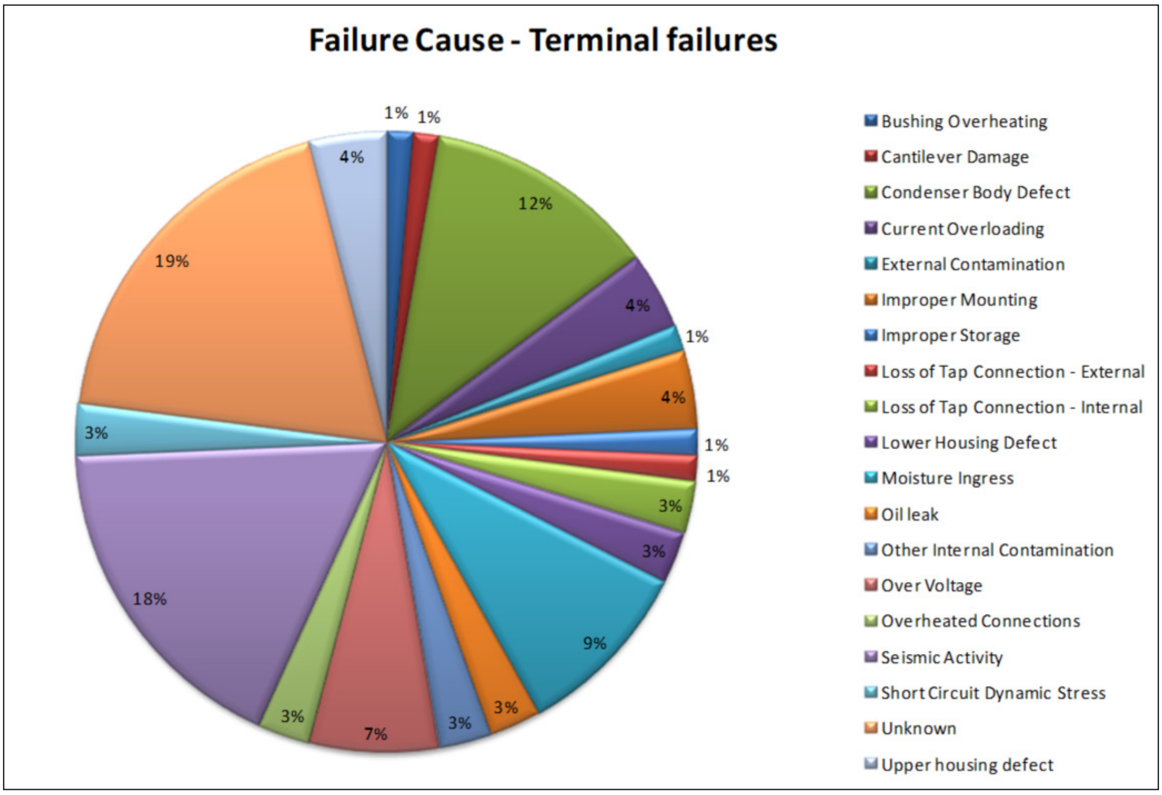


Figure 3.4.1.11: Bushing failure causes based on bushing terminal failures collected

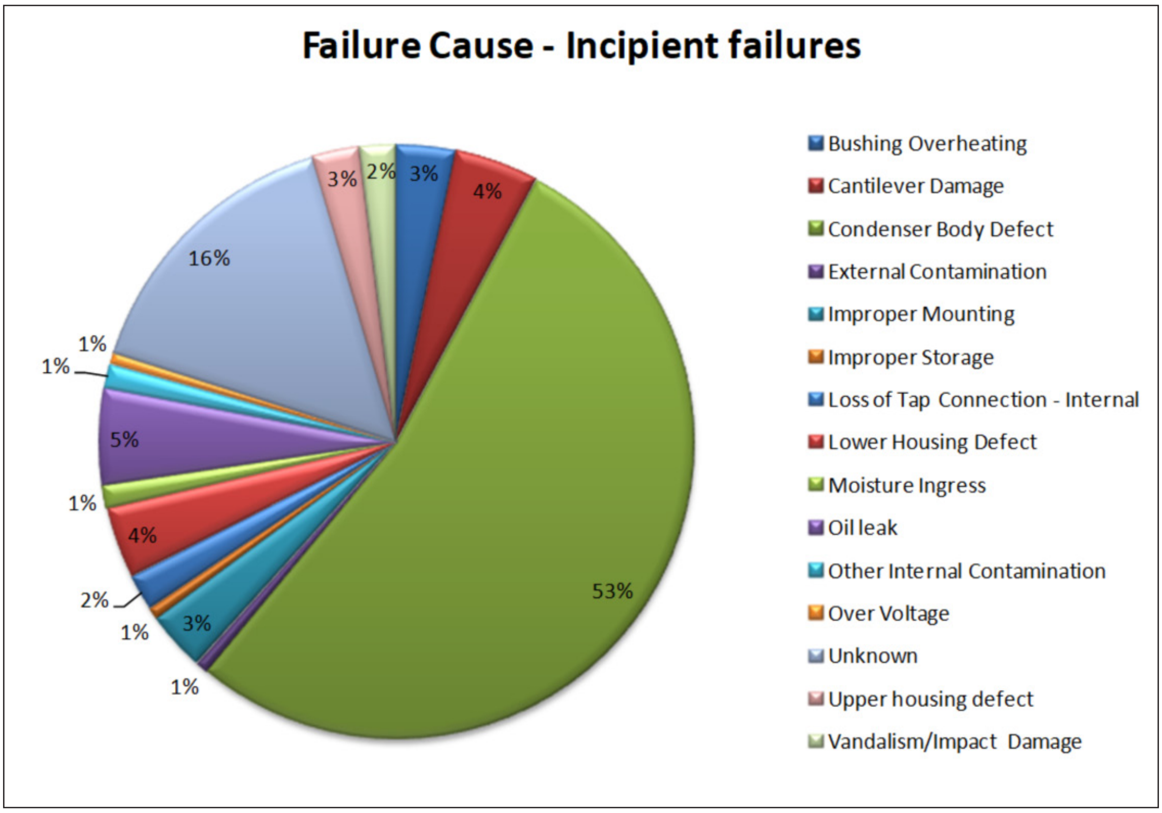


Figure 3.4.1.12: Bushing failure causes based on incipient failures collected

It is interesting that condenser body defect as a failure cause (53 %) is ranked more than four times more abundant in the case of incipient bushing failure than in terminal bushing failure. One possible explanation is that the condenser body defect can be efficiently recognized by bushing diagnostics. Oil leaks make up 5 % and cantilever damage and lower housing defects 4 %. It is also very interesting that moisture ingress is ranked very low (1 %). Perhaps, in a lot of cases, moisture ingress is mixed with condenser body defect as a failure cause.

One of the most undesirable bushing failures is caused by internal breakdown because of the consequence to the transformer. Appearance of internal breakdown types is shown in Figure 3.4.1.13.

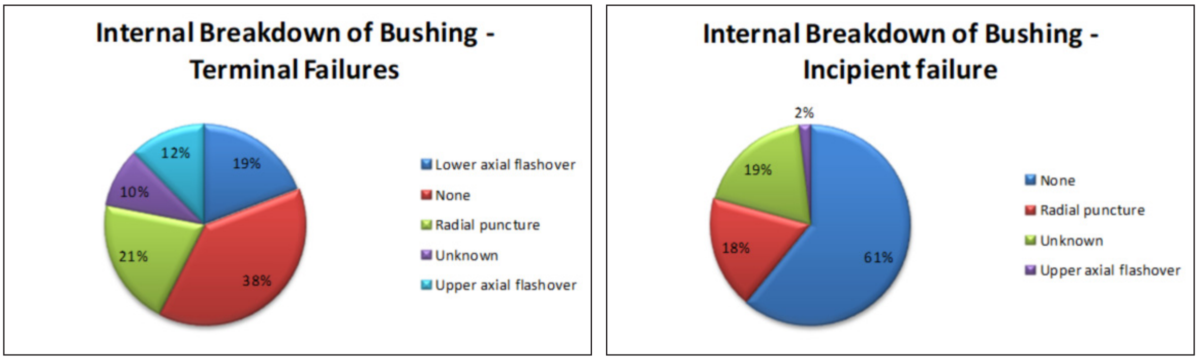


Figure 3.4.1.13: Bushing internal breakdown types for terminal failures (left) and incipient failures (right)

For bushing terminal failures 31 % of the events are declared as axial flashover/breakdown and 21 % as a radial puncture. For bushing incipient failures, 18 % of the events are declared as radial puncture but only 2 % as axial flashover. A possible explanation for this difference is the fact that radial puncture (in its initial stage) is easier to recognize with bushing diagnostics than axial bushing defects that can lead to axial flashover.

For bushing on-site condition diagnostics, a lot of methods are used, refer to chapter 5, and they are essential in preventing bushing terminal failure. It is very interesting to rank these diagnostic methods according to their “effectiveness” in indicating bushing failures, Figure 3.4.1.14.

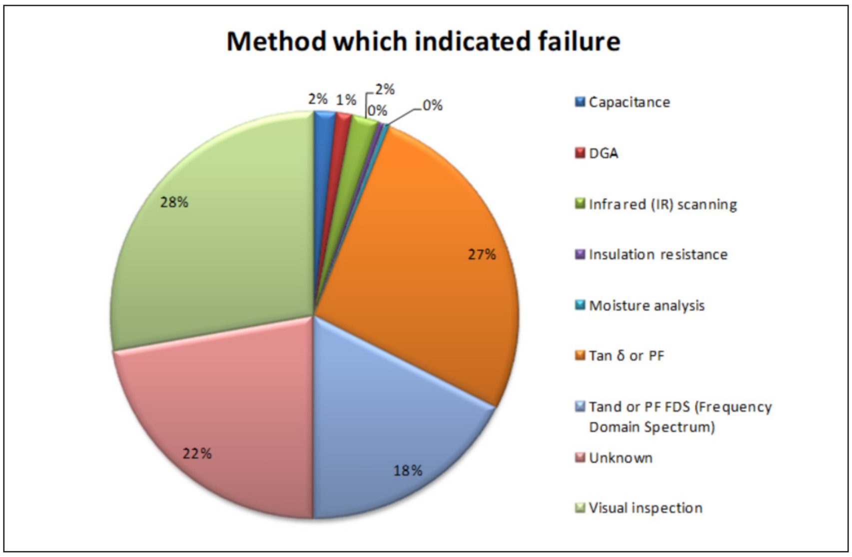
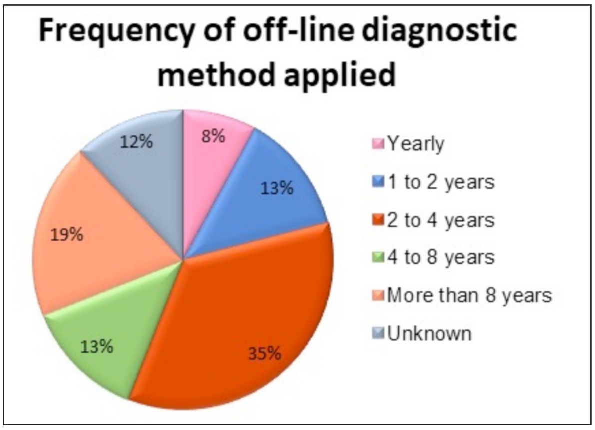


Figure 3.4.1.14: Bushing diagnostic condition methods that indicate failure

The most “effective” diagnostic method which actually indicates incipient failure is tanδ or PF (together with classic and FDS approach) in 45 % of the cases followed by visual inspection in 28 % of cases. It is interesting that bushing capacitance and IR scanning are ranked very low, at 2 % each. The likely reasons that bushing capacitance is ranked low is that capacitance is measured at the same time with tanδ or PF, and there is a lack of diagnostic decision criteria (especially for RBP bushings). The reason that IR scanning is ranked low perhaps is that overheating at the top bushing contact (which is the most probable IR finding) is not considered as a failure at all because of the simplicity of solving this problem.

The most common diagnostic method applied was still off-line (periodic) in 83 % of cases. In 12 % of the cases no diagnostic methods are applied and in only 3 % both on-line (continuous) and off-line methods are used (results are similar for terminal and incipient failures). The frequency of off-line diagnostic methods and visual inspection are in Figure 3.4.1.15.



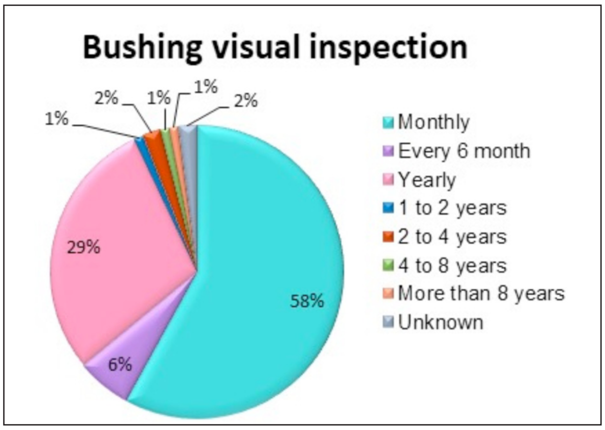


Figure 3.4.1.15: The frequency of bushing off-line diagnostic methods (left) and visual inspection (right)

In more than half of the cases (56 %), off-line diagnostic methods are applied in up to 4 year intervals and in 32 % more than 4 year intervals. In more than a half of the cases, visual inspection is performed monthly (58 %) and in more than 90 % of the cases, it is performed up to the yearly interval.

It is interesting to note that bushing off-line diagnostic frequency is significantly larger for cases corresponding to bushing incipient failure (66 % up to the 4 years interval) than for bushing terminal failure (36 % up to the 4 years interval). These facts reveal that bushing diagnostics help in the prevention of terminal failures.

3.4.2. Q2 data and analysis

Q2 deals with bushing failures that occurred during transformer acceptance test (TAT) in the transformer factory test bay.

Summary of Q2 data - 99 failures are recorded among about 44.000 bushings. It should be mentioned that the population reference period data are inconsistent, similar as for Q1. In 6 out of 9 responses bushing TAT failure rate are listed. They range from 0,04 % to 0,99 % and it seems that a greater failure rate is associated with higher voltages. Based on the whole population, the bushing TAT failure rate is 0,23 %. Bushing failure rate (number of bushing failed during TAT divided by all of the bushings tested) as a function of bushing insulation types and rated voltage are presented in Table 3.4.2.1 and 3.4.2.2.

Table 3.4.2.1: Bushing insulation types TAT failure rate and abundance in population

Bushing types	TAT failure rate, %	Abundance, %
RBP	No data	0
OIP	0,18	88,7
RIP	0,69	7,3
Solid type	0,12	4
All	0,23	100

It is a bit surprising that RIP bushings have a greater TAT failure rate than OIP. This may be due to relatively small population of RIP bushing. Also, the abundance of RIP bushings is lower than was expected. This may be a kind of “geographic” influence (only 8 countries answered the survey, so a response from a single large country may significantly influence the results).

Table 3.4.2.2: Bushing rated voltage TAT failure rate

Bushing rated voltage, kV	TAT failure rate, %
69-100	0,14
100-200	0,27
200-300	0,17
300-500	0,41
500-700	0,22
Over 700 kV	0,98
HVDC	0,79

Based on Table 3.4.2.2, it can be roughly concluded that the bushing TAT failure rate rises with rated voltage. Bushings can fail on various acceptance tests. The test during which bushing failure occurred and whether that particular test was previously performed are in Figure 3.4.2.1.

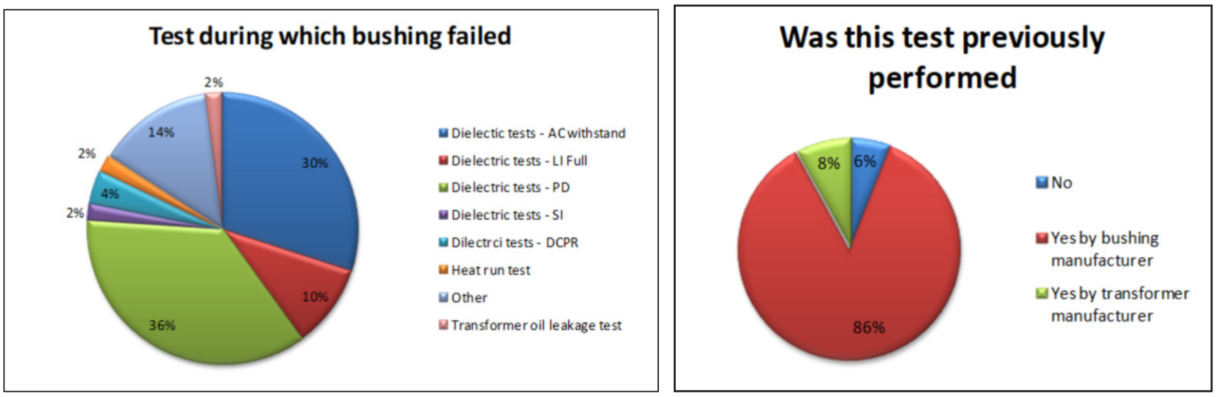


Figure 3.4.2.1: Test during which bushing failure occurred (left) and whether that particular test was previously performed (right)

It is interesting to note that the most frequent bushing failure appeared during PD test (36 %) followed by AC withstand voltage test (30 %) and LI full wave (10 %). 82 % of bushing TAT failures appeared during dielectric tests. In 86 % of the cases, the test during which bushing TAT failure appeared was previously performed by the bushing manufacturer. In 8 % of cases, this test was previously performed by the transformer manufacturer.

The question which arises is - are tests requested by the relevant standards strict enough to take into account the relevant conditions when bushings are installed on the transformer? A revision of IEC 60137 that was introduced in 2008, introduces more vigorous HV bushing tests than in previous standard [3.4.2.2]. The latest version of that standard [2.1] continues with this trend. The analysis of TAT tests during which bushing have failed are analysed based on the year of failure i.e. up to 2009 and after 2009. The percentage of tests during which bushing failure occurred looks similar, with certain decrease of AC withstand and LI full wave failures and an increase of PD failures after 2009. It is recommended that this analysis should be considered as information only, because of the small sample size.

Remedial work duration on the transformer after a bushing failure and the visual appearance of the bushing after the TAT failure are shown in Figure 3.4.2.2.

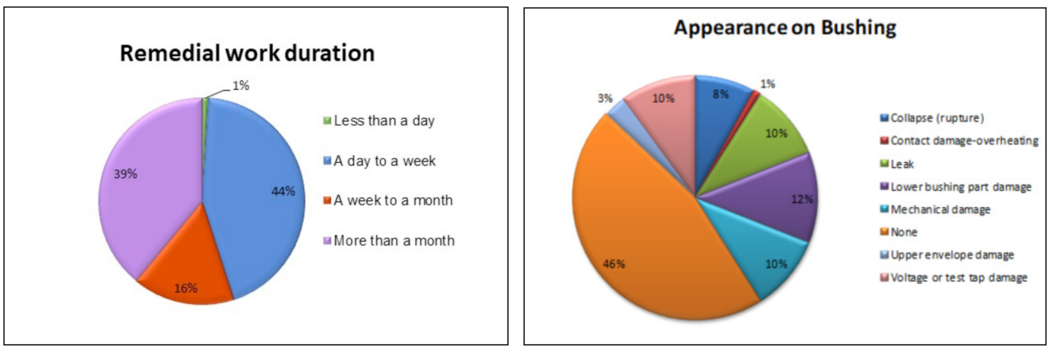


Figure 3.4.2.2: Remedial work duration (left) and visual appearance of the bushing after TAT bushing failure (right)

The foremost often remedial work duration is a day to a week in 44 % of the cases but this is closely followed by more than a month with 39 %. A possible explanation is that the level of pollution and damage of the active part after bushing TAT failure is low (i.e. only bushing replacement is necessary) or high (transformer active part cleaning, dismantling end additional drying is required). Of course, the availability of a spare bushing can also be the reason for a very long remedial work duration (HV bushing delivery time can be several months or more).

Bushing TAT failure cause is shown in Figure 3.4.2.3.

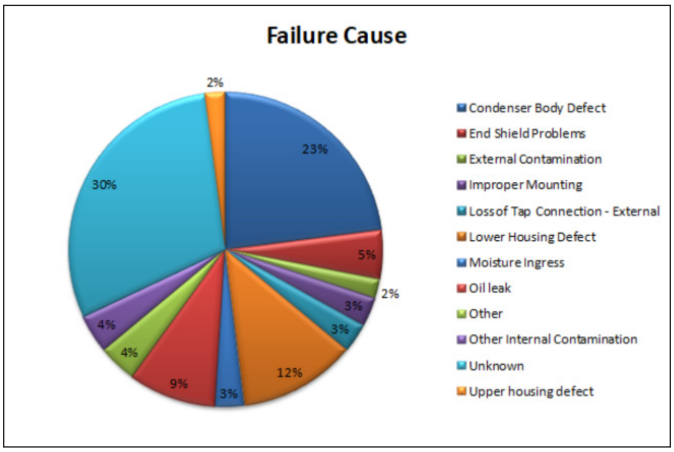


Figure 3.4.2.3: Bushing TAT failure cause

After unknown (30 %), the most abundant bushing TAT failure reason is a condenser body defect (23 %) followed by lower housing defect (12 %), oil leak (9 %) and end shield problems (5 %).

3.4.3. Q3 data

Q3 dealt with bushing in-service failure data from the bushing manufacturers quality records.

In the questionnaire, data was requested regarding AC and DC bushing population, bushing failure rate and an explanation of how the failure rate was calculated. Unfortunately, of seven bushing manufacturers only one gave an exact population with reference period data and a detailed failure rate calculation method. One of the manufacturers did not define the reference period, nor provided a failure rate or calculation explanation; three of them did not define reference period or gave calculation method explanation; one of them defined the reference period and provided a failure rate value but did not explain how the failure rate was calculated.

Six of seven manufacturers provide a bushing storage and maintenance guide to the customer. Five provide a bushing diagnostic guide to the customer and one provides it on the request.

3.4.4. Q4 data and analysis

Q4 dealt with bushing on-site (in-service) diagnostic practice.
Summary of Q4 - 31 responses were received. Utilities can be considered as larger utilities (83 % have installed transformers with a rated power greater than 300 MVA and 17 % have installed transformers with a rated power 64 to 300 MVA, all utilities except one have a voltage greater than 200 kV and more than a third have a voltage greater than 500 kV).

In-sourcing and out-sourcing of diagnostic measurement within the utility is shown in Figure.3.4.4.1.

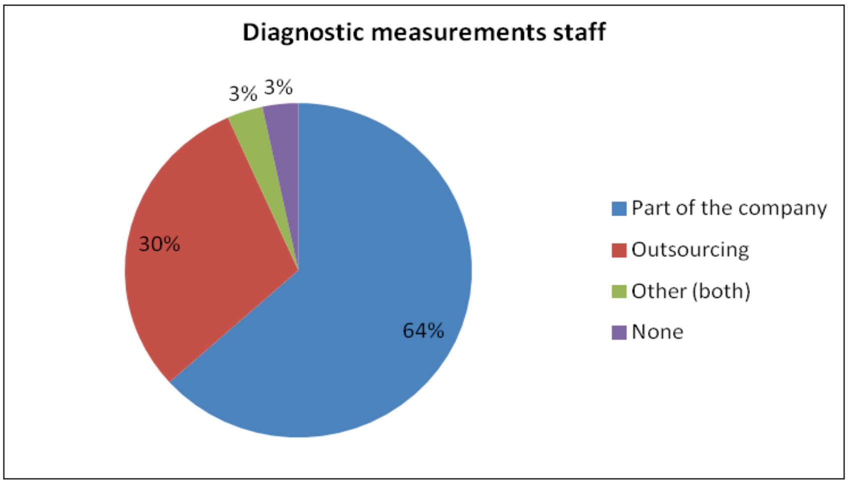


Figure 3.4.4.1: Utility in-sourcing and out-sourcing of diagnostic measurement

The data reveals that in about two thirds of the cases, diagnostic measurement staff are part of the company and about a third is out-sourced. 61% of the utilities have a terminal failure database but only 48% have an incipient failure database. These results are generally as expected.

The type of bushing diagnostic methods, off-line (periodic) and on-line (continuous), applied by the company are shown in Figure 3.4.4.2:

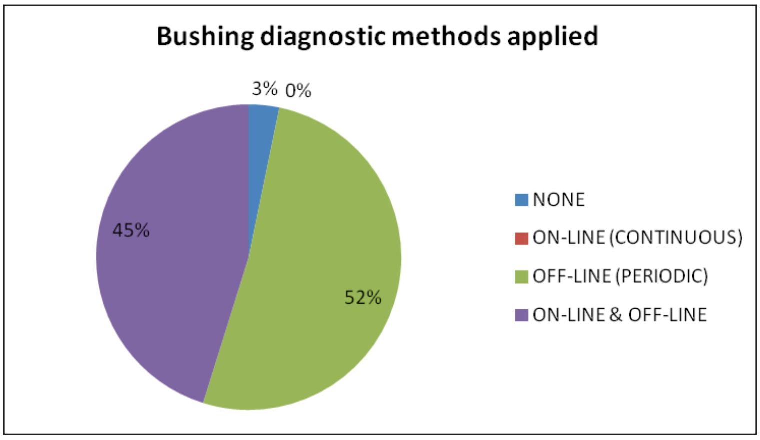


Figure 3.4.4.2: Bushing diagnostic methods applied in the utility

It is interesting to note that 45 % of utilities apply on-line (continuous) and off-line (periodic) diagnostic methods together. There are no cases of applying only on-line methods. Off-line diagnostic methods (alone or in combination with on-line) are applied in 97 % cases. Off-line diagnostic method abundances are presented in Table 3.4.4.1.

Table 3.4.4.1: Off-line diagnostic method usage in utilities

Off-line diagnostic method (periodic)	Abundance (used by utility), %
C and tanδ (or PF)	96,7
FDS	13,3
PDC	6,7
RVM	6,7
PD	33,3
Insulation resistance	36,7
Infrared scanning	76,7
DGA	53,3
Moisture in oil	40
Other	6,7

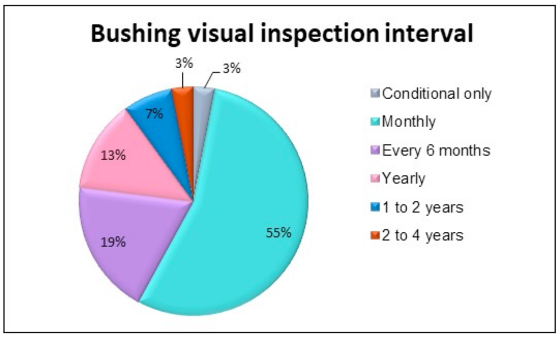
Table 3.4.4.1 reveals expected results. Bushing capacitance *C* and tanδ are the most commonly used off-line diagnostic methods, followed by IR scanning. A bit surprising is that DGA is used in about 50 % of the utilities. Moisture in the bushing oil is used relatively often but only in the cases where DGA is used. Less abundant are the dielectric spectrum methods (FDS, PDC, RVM). Lumped together these methods are used by 16 % of the utilities.

On-line diagnostic method abundances are presented in Table 3.4.4.2:

Table 3.4.4.2.: On-line diagnostic method usage in utilities

On-line diagnostic method (continuous)	Abundance (used by utility), %
Capacitance	92,9
tan δ or PF	64,3
Creepage current	0
Oil pressure	7,1
Voltage transients	21,4
PD	7,1
Other	0

Bushing capacitance measurement is the most common on-line diagnostic method, followed by tanδ (PF). Practically in all cases, tanδ or PF is used together with capacitance measurement. Other methods are rarely used. Measurement of voltage transients is used in about 20 % of the utilities. Bushing visual inspection interval is detailed in Figure 3.4.4.3. In more than half of the utilities (55 %) bushings are visually inspected monthly. Visual inspection up to a yearly interval is in use by 87 % of the utilities. Generally, the data corresponds to Q1, Figure 3.4.1.15.



Note:
Only 4 out of 31 utilities use a different interval for different voltage levels. Only the lowest interval is only presented.

Figure 3.4.4.3: Bushing visual inspection interval

The frequency of the bushing off-line diagnostic methods is shown in Figure 3.4.4.4.

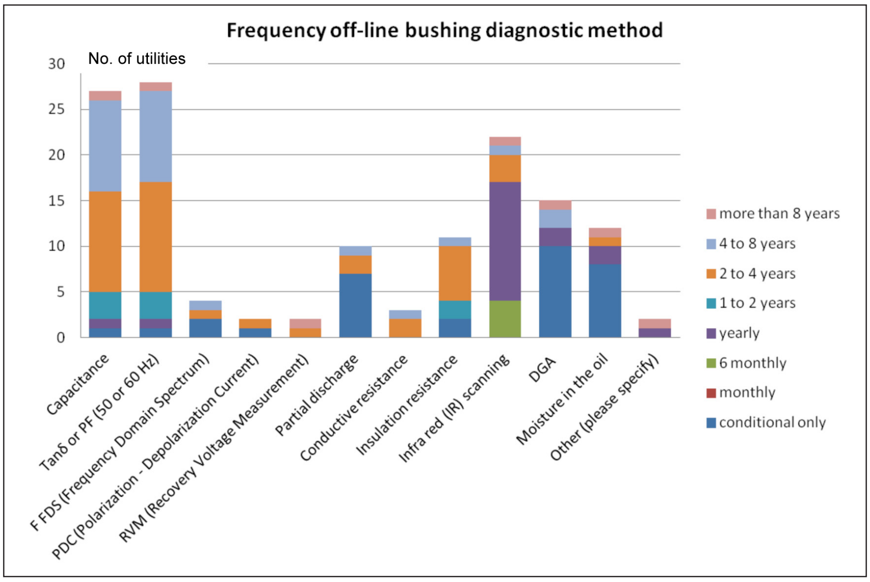
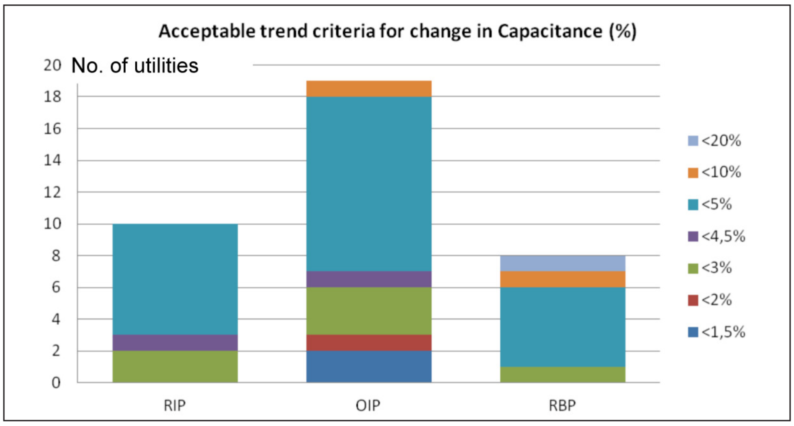


Figure 3.4.4.4: Frequency of off-line (periodic) bushing diagnostic methods

IR is the most common off-line (periodic) method on a yearly interval. DGA, moisture in the oil and PD are often used conditionally. For capacitance C and tanδ are more often used on the interval of 2 to 4 years. Criteria for the acceptable change in capacitance is detailed in Figure 3.4.4.5. A value up to 5 % is the most common for all three dominant bushing insulation types.



Note: Only 3 out of 18 utilities use different criteria for different voltage levels. Only the lowest acceptance level is only presented.

Figure 3.4.4.5: Criteria for change in bushing capacitance

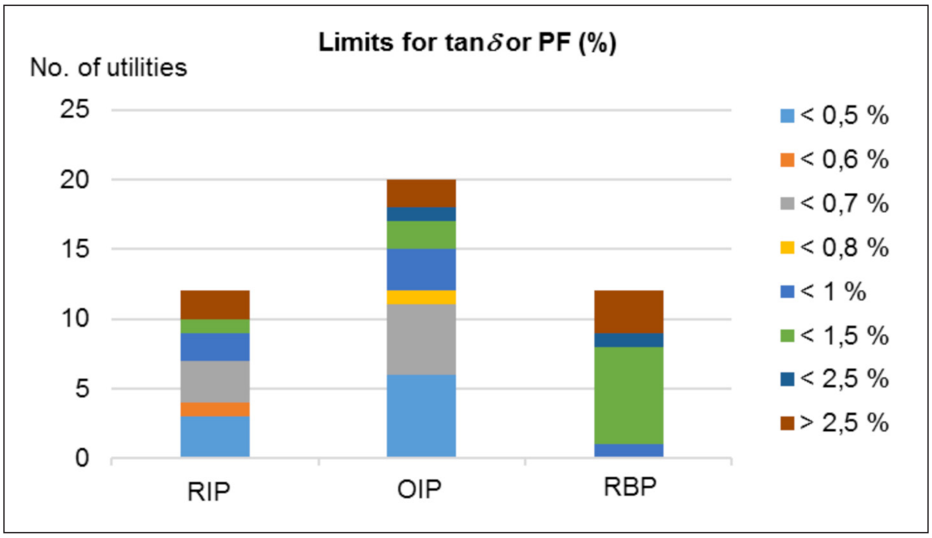


Figure 3.4.4.6: Limits for tanδ or PF

It is interesting to note that for RIP bushings, two thirds of utilities have a tanδ or PF limit up to 1 %. For OIP bushings, three quarters of utilities declared a limit of up to 1 % limit declared three quarters of utilities. For RBP bushings, less than 10 % of the utilities stated a limit of up to 1 %. Also, according to the response, diagnostic decision criteria for OIP bushings are the most familiar to the utilities.

On the question of the most reliable off-line (periodic) diagnostic method, only 17 answers were received (some of them were multiply answers). More than 75 % of the answers is capacitance and tanδ only.

On the question of the most reliable on-line (continuous) diagnostic method to detect bushing failures, only 6 answers were received and all of them were capacitance.

3.5. Survey conclusion

Bushing failures are rarely analysed separately from transformer failures. The consequence is that only terminal bushing failures are normally analysed. Our approach is an attempt to expand bushing failure research to include incipient bushing failures detected with certain diagnostic methods or condition monitoring (Q1). Another goal is to encourage research of bushing failures during transformer factory acceptance testing (Q2). Further goals are to collect bushing in-service failure data from bushing manufacturers (Q3) and to collect data about actual bushing diagnostic practices (periodic or continuous) in utilities (Q4).

These objectives lead to four questionnaires with related responses:

- Q1: Bushing in-service failures: 25 responses from 25 utilities (15 countries).
- Q2: Bushing failures during transformer acceptance testing: 9 responses from 10 transformer manuf. (8 countries).
- Q3: Bushing manufacturer in service failure data: 5 responses from 7 bushing manufacturers (5 countries).
- Q4: Bushing diagnostics, maintenance and failure practice: 31 responses from 31 utilities (16 countries).

The main results are:

Q1: 240 in service failures were collected on more than 101.000 in-service bushings, 73 terminal and 160 incipient. Determining the bushing population is a special problem because utilities usually do not have a list of in-service bushings due to one simple reason - bushings aren't the main asset. Attempts to collect this data from transformer data, see Annex 1, yielded a poor result, probably because of the complexity and time consuming. This make impossible the bushing failure rate calculation in the usual way (i.e. for transformers, [3.2.1], [3.2.2]).

- 67 % of failures are incipient (98 % of outages are scheduled). 70 % of incipient bushing failures results in transformer outage duration of less than a week and only 5 % more than a month. After an incipient failure "no visual appearance" is listed in 65 % of the cases, followed by oil leak at 15 %. Transformer active part contamination isn't recorded. Bushing incipient failure causes are ranked as condenser body defect 53 %, oil leak 5 %, cantilever damage 4 % and lower housing defect 4 %.
- 30 % of failures are terminal (73 % of outages are forced). 31 % of bushing terminal failures results in transformer outage duration of less than a week and 47 % more than a month. The visual appearance of failed bushings is 71 % mechanical damage (11 % with projection of the upper envelope debris). In 30 % of the terminal failures the transformer's active part is contaminated with bushings debris. Bushing terminal failure causes are seismic activity 18 %, followed by condenser body defect 12 %, moisture ingress 9 % and overvoltage 7 %.
- Bushing failure rate increases with rated voltage.
- RBP bushings have a much higher failure rate that OIP and RIP (probably because of their age).
- Results clearly reveal that bushing diagnostics help in the prevention of terminal failures. The most "effective" diagnostic method which indicated failure is tanδ or PF in 45 % of the cases followed by visual inspection in 28 % cases.

Q2: 99 bushing failures at TAT (transformer acceptance testing) was collected among about 44.000 bushings.

- Based on the whole population, the bushing TAT failure rate is 0,23 %.
- Bushing failure rate increases with rated voltage.
- Bushing failure mostly appears during PD testing 36 %, followed by AC withstand voltage test 30 % and LI full wave 10 %. 82 % of bushing TAT failures appear during dielectric tests. In 86 % of the cases, the test during which a bushing TAT failure appeared was previously performed by the bushing manufacturer.
- The most common remedial work duration is a day to a week in 44 % of the cases, followed by more than a month in 39 % of cases.
- The most abundant bushing TAT failure reason is condenser body defect 23 %, followed by lower housing defect 12 %, oil leak 9 % and end shield problems 5 %. 30 % of failures are for unknown reasons.

Q3: The response for this questionnaire, dealing with bushing in-service failure data from bushing manufacturers quality records, was poor and inconsistent. Only five responses from seven manufacturers were received. Six of the seven manufacturers provide a bushing storage and maintenance guide to the customer, and five provide a bushing diagnostic guide to the customer while one will do that on request.

Q4 deals with bushing on-site (in-service) diagnostic practice. 31 responses were received from (in great majority) large utilities.

- 64 % of the utilities use their own staff to perform diagnostic measurement while 30 % out-source.
- 52 % of the utilities apply only off-line (periodic) diagnostic methods, 45 % apply on-line (continuous) and off-line (periodic) diagnostic methods together, and 3 % do not apply diagnostic methods on bushings at all. There are no cases of applying only on-line methods.
- The most common off-line (periodic) diagnostic method is capacitance and tanδ or PF at 97 %, followed by IR 77 %, and DGA 53 %.
- The most often used on-line (continuous) diagnostic method is capacitance, 93 %, followed by tanδ or PF 64 % and voltage transients 21 %.
- The most common criteria for acceptable change in bushing capacitance for all three bushing types is 5 %.
- For tanδ or PF, the common limit is up to 1 % for OIP and RIP and up to 2,5 % for RBP.

The questionnaires, annexures 1 to 4, can be guidelines for future research of this kind but some general recommendations can be provided: questionnaire shouldn't be too complicated and time consuming, and the terminology should be clarified in advance.

The survey method is a powerful tool for failure data collection and analysis. It should be noted that survey results depend on the terms definition (i.e. failure definition), and on the interpretation of the questions, see chapter 3.2. This can cause huge differences when comparing different surveys, such as in transformer failures caused by bushings. A recent opinion is that surveys should be performed on regular basis, for example, in ten years intervals. In this case comparability of results should be assured. A suggestion to accomplish this is establishing a WG to develop standard power system component reliability questionnaires.

4. Bushing failure mechanisms

The aim of this chapter is to explain various failure mechanisms that lead to certain failure scenarios and, if possible, to suggest mitigation measures in the sense of technical or diagnostic advice.

One of the most abundant bushing failure causes described in older references is a certain moisturizing process. In [4.1], service records show that approximately 90 % of bushing failures, that may be prevented, by condition diagnostics and visual inspection, are caused by moisture penetration into the bushing through poor seals or other openings. This statement seems to be valid for OIP bushings and is strongly dependent upon bushing technology, failure definition and utility experience. According to section 3.4.1, moisture ingress is ranked very low from 1 % for bushing incipient failure to 9 % for bushing terminal failure. In spite of the fact that moisture ingress as a failure cause can be hidden in a lot of other failure cases, such a large percentage in older references seems to be overestimated for modern bushings. According to [1.1.3], moisture ingress isn't even mentioned as an abundant bushing failure mode. Some other failure modes are mentioned such as specific problems related to OIP zig-zag technology bushings, top terminal connection problems, copper mobility, bushing draw lead multiple connection caused by switching overvoltages, etc. References [4.1] and [1.1.3] reveal that for some authors in some parts of the world, a certain failure mode may be common, but for another part of the world, the same failure mode may be rare, [4,2], [4.3], [4.4]. Failure modes explained here were gathered through WG member's experience and knowledge so as various references, and we hope that they are representative for a worldwide bushing population.

4.1. Description of failure mechanisms and case studies

Bushing failure mechanisms are derived from four basic phenomena:

- Mechanical
- Thermal
- Electric and dielectric
- Chemical and pollutant

It should be noted that these phenomena are simplified and conditional because failure mode can start from one basic phenomena and depending upon service conditions it can expand to include another phenomena.

4.1.1. Mechanical

Seismic disturbance
The electric utility industry has become increasingly concerned with the loss of condenser bushings due to seismic activity. In the Q1 survey, seismic activity is the reason for 18 % of bushing terminal failures and 6 % of all bushing failures (refer to section 3.4.1, Figures 3.4.1.10 and 3.4.1.11). Bushings, by their physical nature are very susceptible to the acceleration caused by earth quakes because their mechanical resonant frequencies can be close to earthquake frequencies [4.1.1.1]. Their tall thin shape makes them tend to oscillate at frequencies common in seismic motion. Additionally, it can be estimated that transformer tank flexing can double the horizontal acceleration seen at the bushing flange, resulting in bushing damage. The likely location of damage is at the joint between the flange and upper envelope because this joint forms the cantilever rigidity of the bushing. Depending on the design of the bushing, damage can vary. For a cemented upper envelope, the damage is usually either complete breakage or no breakage (no damage at all). For pressure compression joints, the failure is a tilting of the insulator and leaking of the oil. After the failure (leak), the insulator corrects its position and often reseals. However, in more severe cases the insulator moves perpendicular to the axis of the bushing and can't reseal, resulting in a massive loss of oil. To prevent such perpendicular movement, a type of clasp can be used as a useful on-site measure in seismic very active areas [4.1.1.2].

With most cases of seismic damage, the ultimate loss of the bushing is due to the loss of oil. Dry bushings are less susceptible to this due to the lack of internal oil and higher mechanical rigidity. However, the seal between the flange and the condenser is highly stressed during seismic activities and can be compromised allowing moisture to enter the transformer and run down the lower end of the bushing.

Not all bushings are designed for seismically active areas. Calculations can be performed to determine the seismic resilience of a bushing design to this acceleration, and testing which is expensive, can confirm the performance. Today, seismic requirements for bushings are defined [4.1.1.1]. Improved testing programs and calculation methods are being still developed around the world. It can be concluded that bushing seismic resistance has significantly improved in recent decades.

Vandalism

Bushings are a visually prominent part of the transformer and are a frequent target to vandals. In most cases this term assumes shooting of bushings with a kind of a weapon. Bullets with its high impact energy can destroy upper envelope or even condenser body inside. Porcelain is the most fragile in that sense. OIP type bushings with pressure compression joints and porcelain upper envelope will usually collapse in the case of porcelain break - they are sensitive to vandalism. For cemented upper porcelain envelope resistivity is a bit better – oil will leak but collapse may not happen immediately. The most resistant to vandalism are dry type bushings with composite upper envelope because it can withstand much higher impact energy than porcelain, and in lots of cases, service can be continued for a limited time. Nowadays vandalism becomes frequent reason for bushing failure, especially in some countries, [1.1.3], [4.1.1.3]. Unfortunately, number of countries “suffered” from this phenomenon increases rapidly.

Rigid bushing connection to the switchyard

When bushings are connected to the switchyard by a rigid tubular connection, the rigid connection can cause a bushing failure. It was found that an abundance of bushing terminal failures (explosion) and incipient bushing failures (bushings replaced in service because of the increased value of tanδ measured on site) where bushings are connected to the switchyard by rigid tubular connection is high, Figure 4.1.1.1, [1.1], [4.1.1.4]. A possible reason for such behaviour is the mechanical forces on the top of a bushing caused by aluminium tubular connection thermal dilatation. Visual inspection of exploded bushing debris shows that the failure mechanism is relates to moisture ingress, loss of oil and/or test tap deterioration with arcing as a consequence, Figure 4.1.1.2. Breakdown trace analysis revealed radial and, in some cases, axial bushing condenser body breakdown. Failures happened after approximately 10 years of service and often with fire as the consequence.

The application of a dilatation compensator, Figure 4.1.1.1 is not a good solution for reducing mechanical forces at the top of a bushing because:

- Dilatation direction and compensator orientation are not always aligned (sometimes it is difficult to align them properly)
- Dilatation compensator often becomes blocked (seized) after years of service

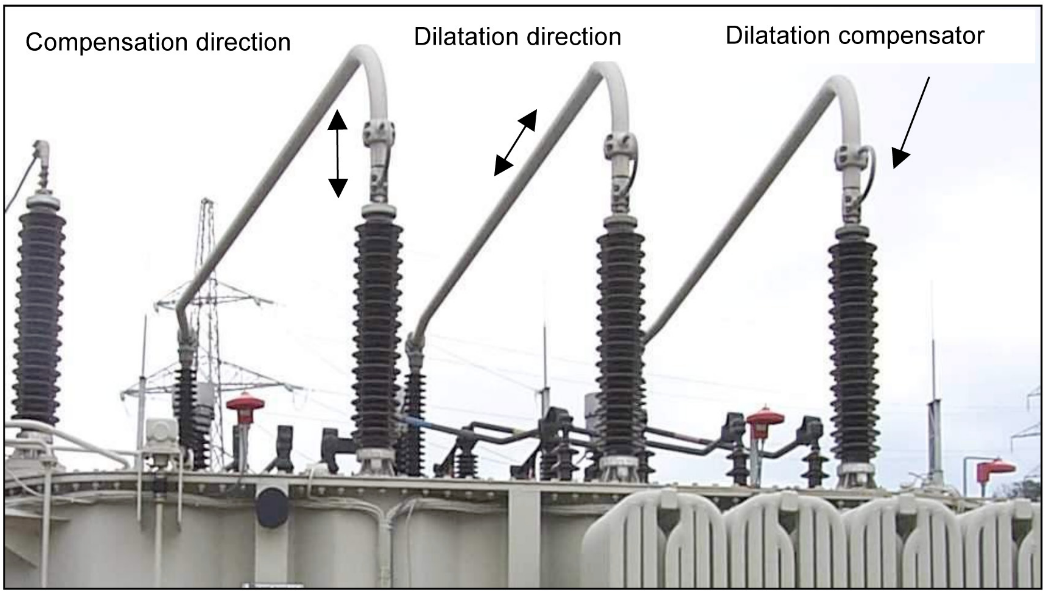


Figure 4.1.1.1: Tubular bushing connection with dilatation direction and dilatation compensator assigned

Figure 4.1.1.1 shows a 123 kV transformer connected to the switchyard by the use of a rigid tube. Dilatation compensators are aligned in the wrong (vertical) direction and thermal dilatation of tubular connections are aligned in horizontal direction. A similar situation is shown in Figure 3.1. where left 420 kV bushing exploded. The intact right bushing was replaced several years earlier due to tanδ rising.

Figure 4.1.1.2: Arcing traces on last electrode and tap elements

The best prevention from this type of bushing failure is a flexible connection to the switchyard using flexible conductor (rope) or similar. Measurement of capacitance and tanδ are good measure for diagnostic prevention.

Note:

It was reported in several cases that transformer fire protection equipment (firefighting system, water spray system) is not able to extinguish the transformer UHV bushing fire because bushings (due of their large size) are out of the protection's effective operating range, as shown in Figure 3.1, where the water spray nozzles are directed at the transformer tank and not towards the bushings.

Electrodynamic forces on bushing transformer part
One of the causes of bushing transformer part (or oil part) damage are electrodynamic forces that occur during a short circuit, be it while testing or in-service. Of course, the problem is more often related to LV rather than HV bushings. The visual appearance of these failures are oil leaks and cracks of oil part of the bushings. It should be noted here that electrodynamic forces, in normal cases, are not essential problem for bushings. The problem is the movement of the leads in the transformer due to electrodynamic forces, especially if the lead can hit the bushing's lower end. This can act as an impact that can damage the bushing. Good prevention is the appropriate fixation of leads in the vicinity of the bushing. In the case of draw-lead bushing (especially with solid copper lead) the usage of mechanical "pillow" between the lead and bushing lower end prevents lead movement relative to the bushing and absorbs the impact energy.

4.1.2. Thermal

Gas bubble evolution

When oil and a gas, such as air or nitrogen, is confined in a fixed volume space, such as in a bushing, pressure equilibrium is reached over time at any given temperature. If the temperature changes, the volume of the oil changes and the gas space changes accordingly. When this occurs, three variables come into play. First, the gas pressure changes with the volume change. Second, the gas pressure changes with the temperature of the gas. Third, the ability of the oil to absorb gas varies with temperature. As a result, with constant fluctuations in temperature there is continuous change in the amount of gas dissolved in the oil. If the temperature rapidly decreases after being high for some time (for example because of very rain intensive shower), the gas cannot escape quickly enough to avoid the formation of bubbles in the oil. In a bushing, this can, and does occur in areas of high dielectric stress causing partial discharge or even complete breakdown, [4.1.2.1].

In most cases, bushings in service are not stressed enough to fall victim to this phenomenon and do not often experience the sudden drop in temperature needed to create bubbles. Where these bubbles are an issue is in the transformer factory when dielectric tests at higher than service voltage follow a temperature rise test after which rapid cooling occurs. This is further aggravated if transformer overloading tests are performed. The result is often seen as a partial discharge in the bushings and in some cases complete breakdown. No bushing with a fixed oil/gas space is exempt from this phenomenon as it is pure physics, but some bushings are more problematic than others due to the gas/oil ratio and the configuration of the condenser.

Current path and contact problems

This failure scenario deals with a top terminal contact problem which often leads to the so-called multiple contact problem in draw-lead (flexible conductor) bushing type. There is always a small voltage difference between the draw-lead and the bushing's central tube. The difference is due to the resistance of the rope, and the contact resistance of this rope's connector to the bushing's upper contact. The central tube does not carry any significant current and thus has no voltage drop along its length. This voltage drop can rise drastically if the bushing suffers from a top terminal contact problem. This failure scenario seems to be common. Tilted bushings are a bit more susceptible to this than vertical ones. Very fast transients (VFT), together with vibrations, may play a certain role in the initial stage and development of this failure scenario [3.2.8]. The most drastic case studies follow.

A 245 kV bushing failure in the form of an upper envelope and lower bushing part explosion occurred on an approximately 25 years old transformer, [3.1]. It was accompanied by mechanical damage to other bushings and a small-scale fire on the transformer, Figure 4.1.2.1. Upper envelope fragments destroyed the neutral bushing and one 420 kV bushing sustained damage. Visual inspection of the bushing indicated a radial condenser body breakdown. Inspection of the bushing revealed poor contact on the screw of the upper connection. The connector body itself showed signs of overheating which, enhanced during service, resulted in the melting of the brazed joint by which the copper cables were fixed to the connector body (Figure 4.1.2.1, in the middle top and bottom). Physical separation of the connector body and the cables occurred. Conduction of the current from the connector body was taken over by the central bushing tube causing severe central tube and bushing condenser body overheating, and finally breakdown.

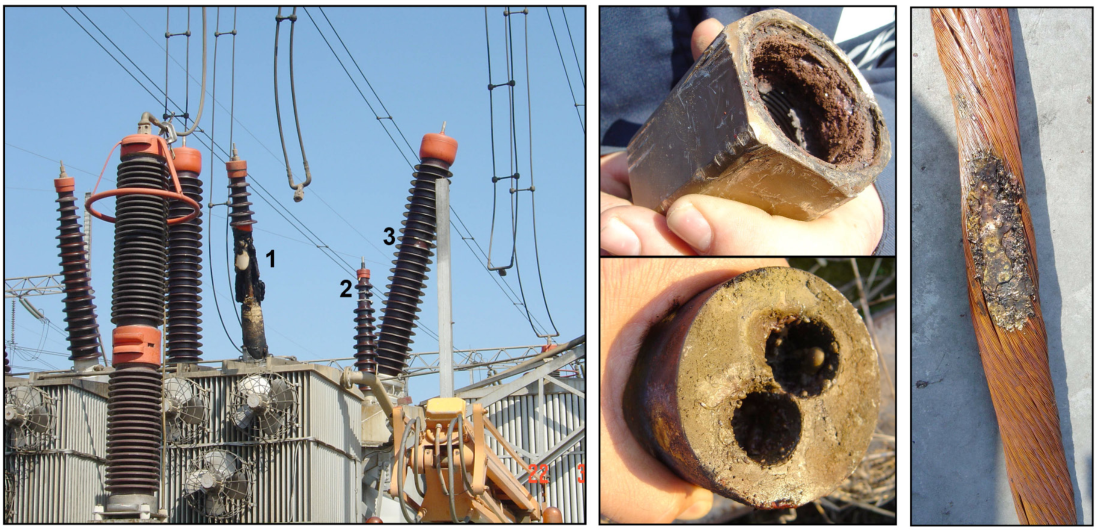


Figure 4.1.2.1: A 400 kV transformer failure; left: 1 - burst 245 kV bushing, 2 - destroyed 170 kV neutral bushing, 3 – damaged 420 kV bushing; middle top: traces of overheating on the top connection; middle bottom: connecting bolt body torn off cables; right: melting trace of brass central bushing tube on the copper rope

A bit less extreme but generally the same failure scenario is shown in Figure 4.1.2.2., [4.1.2.2].

A 300 kV bushing failure occurred on 700 kV transformer, age 35, with the bushings installed at angle of 40 °. The air side porcelain was completely broken off and a rupture of the bushing in the level of flange extension occurred. The bushing failure ignited a fire. Previously, moderate overheating of the upper terminal was noticed but no remedial actions were taken.

Figure 4.1.2.2: 700 kV transformer failure; top left: 300 kV failed bushing, top right: intensive thermal degradation of paper near central tube, bottom: breakdown traces on the outer side of central tube (left) corresponds to arc traces on the inner side of the tube

The failure scenario is similar to the previous case: poor contact on the top of the bushing increased the voltage between the rope and the central tube causing arcing that heats the central tube. The consequences are bushing overheating and finally radial breakdown.

These two cases clearly show how an incipient failure develops into a terminal failure, and how the absence of bushing condition diagnostics leads to terminal bushing failure, accompanied by great costs and long down-time.

Some service evidence shows that (especially in cases of a heavily loaded transformer installed in hot climate) the electrical contact of the rope with the central tube can generate additional heat inside the bushing that, in the long run, can jeopardize the bushing's insulation. It is interesting to note that in the case of multiple contacts, the total conductive losses in the bushing is a bit lower than in healthy stage but the losses are more concentrated in each point of electrical contact between the rope and the central tube. This causes overheating. According to experience, the most severe situation appears when the contact of the rope with the central occurs near the bushing flange, probably because of the most difficult cooling. Poor contact on the top of the bushing may increase and speed up bushing deterioration.

The rope is traditionally insulated with a few layers of cotton tape to insulate for the small voltage between the draw-lead and the central tube. Improving the mechanical and dielectric strength of this insulation will help to minimize the risk of this failure scenario. In [3.2.8], one millimetre of thermally-upgraded insulation is suggested.

The most effective in-service mitigation measure for this failure scenario is bushing thermal image scanning and winding resistance measurement. When a problem is suspected (especially in the case of draw flexible lead and inclined bushings), DGA (transformer oil, bushing oil – if appropriate) may provide additional information about the presence of arcing or overheating. Of course, bushing tanδ will increase if the insulation is heavily aged. Note that the ageing of bushing insulation is never uniform throughout the condenser body, and that the tanδ increase is often smaller than expected. Capacitance change will occur at the final stage or with elevated temperature.

4.1.3. Electric and dielectric

One of the most undesirable bushing condenser core problems is cracking or delamination. This problem represents the loss of integrity of the condenser core.

Core cracking or delamination

All three insulation types of bushings (RBP, OIP and RIP) suffer from this problem but in different ways and with different causes.

- RBP

Resin bonded paper condenser bushings often suffer from cracks. Cracks can arise from an imperfect manufacturing process or in service caused by thermal or mechanical issues, Figure 4.1.3.1 (refer section 2.1 and chapter 6).

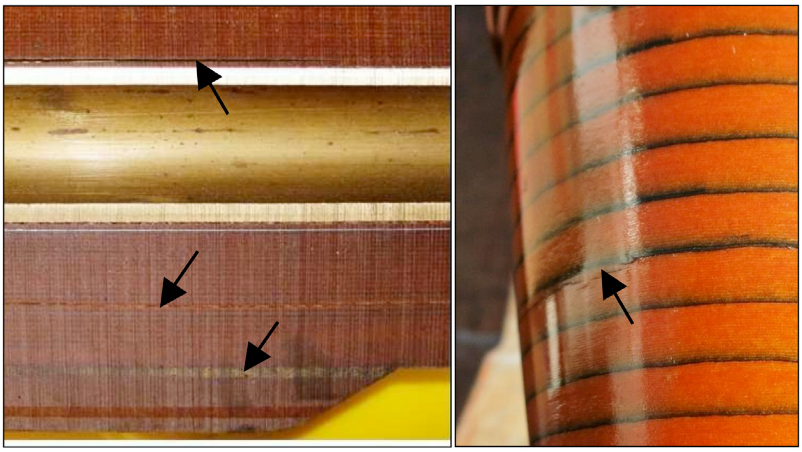


Figure 4.1.3.1: Cracks in RBP bushing condenser body marked by arrows; left: bushing axial cross section, right: bushing lower part

It can be said that cracks are more or less inherent to RBP technology. The cracks and trapped air are probably the main reason for the relatively high level of PD. At the initial stage, no significant changes in bushing capacitance and tanδ are observed but after a certain service period capacitance starts to increase due to penetration of the oil into the condenser body (oil has about a 2,2-times larger permittivity than air). This oil penetration is not a serious problem if it is uniform throughout the condenser body, but cracks appear randomly rather than uniformly, Figure 4.1.3.2. That means that the capacitance of some of the elementary condensers increases (C_{1i} – in Figure 2.1) while some others remains the same. This disturbance in the capacitance chain will lead to a voltage distribution disturbance (voltage increase on the elementary condensers that are not affected with cracks and oil penetration) resulting in PD rise and thus a reduction of the bushing's life, and finally bushing breakdown. It should be noted that maybe the most dangerous phenomenon in condenser bushings - shortening of capacitance chain by breakdowns of elementary condensers results in a capacitance increase. It is practically impossible to determine the origin of an RBP bushing capacitance increase based on periodic on-site diagnostic measurement because both of these effects may have very small influence on the tanδ value. It seems that (on-line) continuous diagnostic measurement can distinguish these phenomena: oil penetration causes a slow rise of capacitance compared to elementary condenser breakdown which causes a sudden (steep) rise of capacitance.

Figure 4.1.3.2: Two examples of oil penetration into RBP bushing condenser body (darker area)

- OIP

Similar to other condenser type bushings, OIP bushings are produced by the winding of paper (or synthetic for RIS) sheet with insertion of electrodes in certain places, Figure 2.1.1.1. This winding should be as tight as possible to avoid scissoring between the paper and the electrode sheets. Gluing is used rarely and sparingly. To the contrary resin in RBP, RIP and RIS bushings acts as glue between paper or synthetic layers. If paper sheet(s) are wounded loosely, they can move axially. In normal cases, this movement rarely happens, but some facts may favour this, such as exceptional overloading (overheating) and the winding of the bushing with more than one sheet of paper width in axial direction.

Figure 4.1.3.3: Axial destruction of OIP bushing (layer sliding) probably because of poor paper sheet overlapping

Exceptional overloading (above than according to [4.1.3.1]) can overheat paper in the vicinity of the bushing conductor up to the stage that the paper will lose its mechanical properties and reducing friction. It is assumed that such intensive ageing will affect the bushing's tanδ and capacitance also in severe cases, and especially at elevated temperature. It should be noted again that bushing insulation does not age uniformly (e.g. paper in the vicinity of the central tube or conductor age faster than paper in the outer layers).

High voltage bushings may be very long (more than 10 m) and it is difficult to produce a sheet of paper width that corresponds to this length. Due to this, high voltage bushings are often wound with more than one paper width making up the width of the condenser. There are several ways to apply paper sheet axial "overlapping". This overlapping can be a weak point. Figure 4.1.3.3 shows the axial destruction of an OIP bushing active part after a terminal failure accompanied with fire (refer to Figure 3.1). It appears that some layers of the condenser body slid on to one another. Also, a sheet of paper overlapping is at the same axial position of the condenser body and that is probably a weak point. Examination of previous periodic diagnostic measurements [4.1.3.2] reveals that progression of this failure mode is fast. Thus, for prevention of this failure mode, a continuous on-line monitoring system seems to be much more effective than periodic measurement. It can be recognized with capacitance and tanδ rise, and oil pressure rise just before failure. DGA will show arcing in the insulation system.

- RIP

Resin impregnated paper condenser bodies can crack or delaminate because of mechanical, thermal (including thermal dilatation or shrinkage) and electrical overloading, or due to the improper manufacturing technology, or their combination. Figure 4.1.3.4 shows delamination of a RIP bushing, in the advanced stage, after 12 years of bushing service. Capacitance rise was about 25 % and tanδ rise from 0,34 to 0,59 %. Data shows that in this case the bushing capacitance is more sensitive to the delamination process than tanδ.

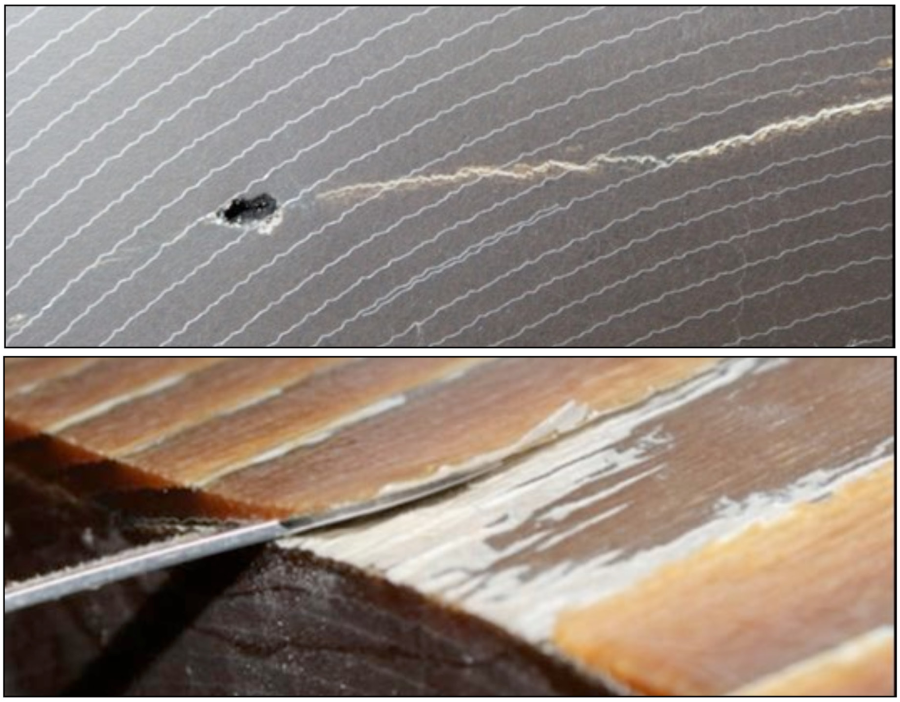


Figure 4.1.3.4: RIP condenser body crack; up: condenser body cross section with breakdown cavity and delamination; down: delamination in advanced stage

It was reported that high temperatures (severe overloading) can trigger the delamination process. The background for this phenomenon is briefly described in [4.1.3.3]. If the resin temperature exceeds its glass transition temperature, it will instantly change into a new material and after cooling it will never turn back to normal resin. Even when only a part of the bushing's body exceeds this temperature, it may result in voids, cracks and the formation of by-products that can cause PD and/or breakdown. It is interesting to note that if PD in a RIP bushing starts, it will never end. Unlike OIP, RIP have no ability to recover after low-level PD.

Technological reasons that may contribute to cracks are a poor aluminium foil surface or an improper casting process, especially the shrinkage process during the curing of the resin. The appearance of this crack is often on the surface of the aluminium (Al) foil, as is shown in Figure 4.1.3.5 or on right side of upper Figure 4.1.3.3

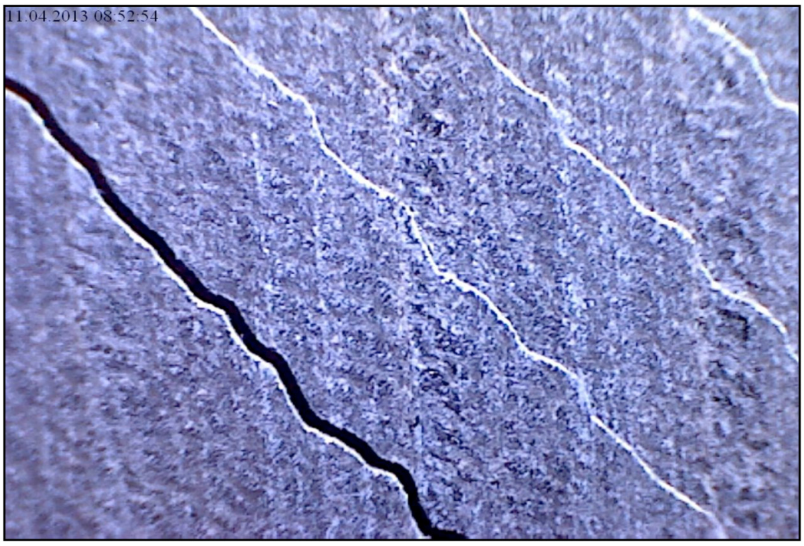


Figure 4.1.3.5: RIP condenser body crack probably caused by technological reasons

Electrode end problems

From a theoretical point of view, the highest electrical field in the bushing condenser core is somewhere near the electrode's ends. This is one of the most common locations and reasons for unsuccessful bushing FAT. This is true for all condenser bushing types (RBP, OIP, RIP and RIS).

For technological reasons and tolerances, electrodes are not ideal and smooth cylinders made of very thin material with strictly defined end radii. The electrode's edge circumference always has some sharp edges or a poor overlap of the electrode can appear. Electrode overlap is never ideal – which means – that the axial position of the electrode's edge changes slightly along its circumference. The electrode's axial position also varies slightly compared to the calculated position. The consequence is a higher electrical field than that calculated for an ideal geometry. Regarding these phenomenon, two technologies should be distinguished: painting of the bushing's electrodes with conductive paint versus inserting conductive layers (mainly Al foil). It seems that electrode painting technology is related only to OIP and it is slightly more precise than insertion technology. To the contrary, electrode insertion technology is used for all condenser bushing types. During the history of bushing technological development, many measures were applied to minimize this problem (foddering and additional foddering of foil ends, special foil inserting by use of special calibration system, ...). Despite this in-service bushing failures related to the bushing's electrode end and improper overlap, still exist. It seems that this problem increases with bushing size – especially diameter.

Figure 4.1.3.6 shows a puncture at the last condenser foil overlap, representing a RIP bushing failure after about two service years [2.1.4]. The bushing's continuous monitoring system registered an instantaneous capacitance change of about 3 %. This capacitance change was confirmed with a capacitance measurement after de-energization and dismantling. It is interesting that tanδ shows no noticeable change after the failure compared to the bushing's FAT results. This puncture is probably caused by poor overlap of the last condenser foil. Another possible cause could be the improper handling of the crepe paper condenser body after winding and before treatment with resin. At this stage, the condenser body is very weak, and can be very heavy requiring it to be handled with special care. This handling problem affects the outer layers much more than the inner layers.

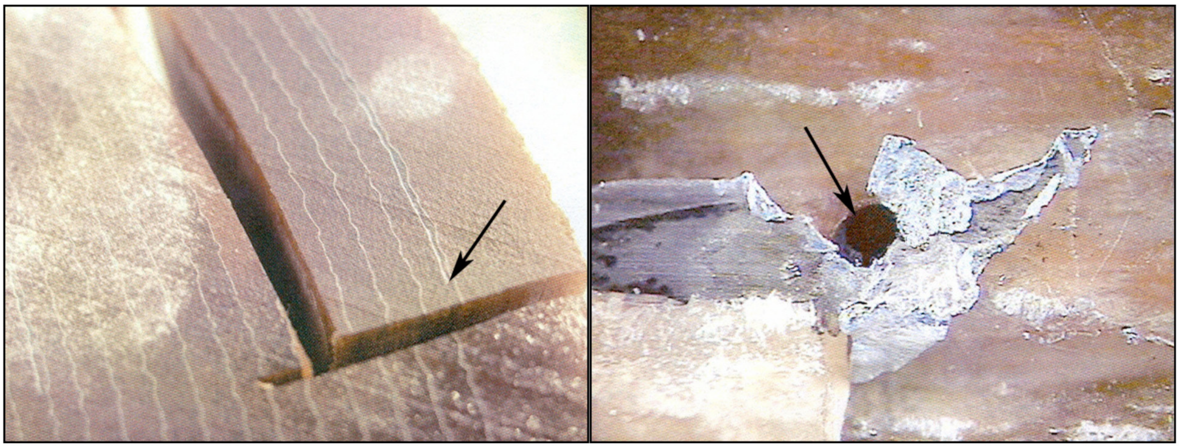


Figure 4.1.3.6: RIP condenser body puncture (marked by arrows) placed in vicinity of bushing last foil overlap (left); puncture traces represents hole about 0,5 mm in diameter (left, captured by microscope with magnification x 15)

As already stated, all three types of bushings suffer from the electrode end problem. Figure 4.1.3.7 shows partial breakdowns (breakdowns between electrodes) at the oil (lower, transformer) portion of a RBP (left) and an OIP bushing (right).

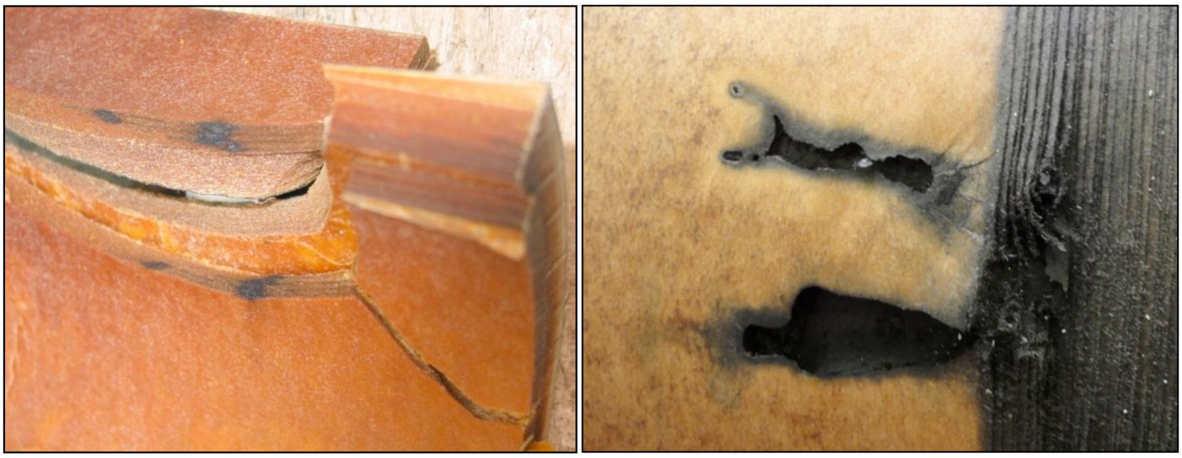


Figure 4.1.3.7: Lower part of RBP condenser body partial breakdown (left); lower part of OIP condenser body partial breakdown (right)

Effective diagnostic methods for detection of this problem are PD and capacitance measurement. First mentioned in early stage of the problem and second when breakdown between electrodes already appears. tanδ results may be affected but often they are not.

Zig-zag or lined Ink condenser bushings

For a period of about three decades, condenser bushings were produced in North America with as many elementary capacitors as thought practical, by the use of lines of conductive ink printed on the paper to make condenser bushings, Figure 2.1.1.2. There were thousands of lines in each condenser. These lines were printed on the surface of the paper in a zig-zag (also referred to as herringbone) pattern from top to bottom only a few millimetres apart. To insulate the turns of paper from each other and to provide insulation at the ends of the lines, the paper was wound two sheets at a time with only one having lines. The plain sheet (no ink) was cut to be longer at the ends than the zig-zag printed paper resulting in an oil-filled gap at the end of each line of the condenser. For reasons which have been debated for the past 25 years, partial discharge often begins at this area and begins to damage the condenser by shorting out the lines at the bottom end. This results in a rise in power factor (tand) and, in many cases, complete dielectric breakdown. The reason this condition is so dangerous is that the increase in losses is not linear with time. Bushings which appear to a have stable power factor (tand) can suddenly increase to failure level in a short time. This condenser design with ink-lined paper and plain kraft paper thus created a gap at the ends of the active layers in the condenser core where the manufacturing cutters sharply sliced off the lined paper. This gap is filled with oil. A heavily loaded transformer will generate heat internal to the bushing thus subject the bushing to a higher immersion-oil temperature, and consequently, increase the internal temperature. The heated bushing oil expands and intensifies the pressure in the confined gas space which causes an increased quantity of gas to become dissolved in the oil. Cyclic ambient temperature and loading allows heating and cooling of the bushing oil. As the oil cools, it contracts, reducing the pressure in the gas space of the bushing head. If the pressure reduction occurs rapidly enough, the gas-saturated oil will develop a tendency to produce bubbles of gas. This evolution can occur in the highest electrical stress regions of the bushing, normally at the inboard end in the gaps mentioned above. A critical combination of gas bubbles and dielectric stress causes partial discharges to occur within this gap and the lined ink layers are damaged and become shorted together. Over time this increases the power factor of the bushing. The deterioration, once started in these cases is very exponential, often leading to electrical failure and rupture of the bushing.

Test tap problems

In spite of the bushing failure survey results, where a test tap contact problem as a failure cause is ranked low, only about 2 %, see Figure 3.4.1.10, test tap problems are often discussed between experts. The likely reason for this is the fact that as part of each off-line bushing capacitance and tanδ diagnostic measurement, the test tap is used and carefully inspected. The most commonly recorded non-conformities are:

- Contact problem inside bushing (poor contact between test tap and last bushing electrode)
- Contact problem outside bushing (poor test tap grounding)
- Oil leak
- Moisture ingress into test tap often followed with corrosion

Poor contact inside bushings is often recorded thorough tanδ (or PF) measurement. If tanδ decreases while measurement voltage increases, suspect poor contact, Figure 4.1.3.8.

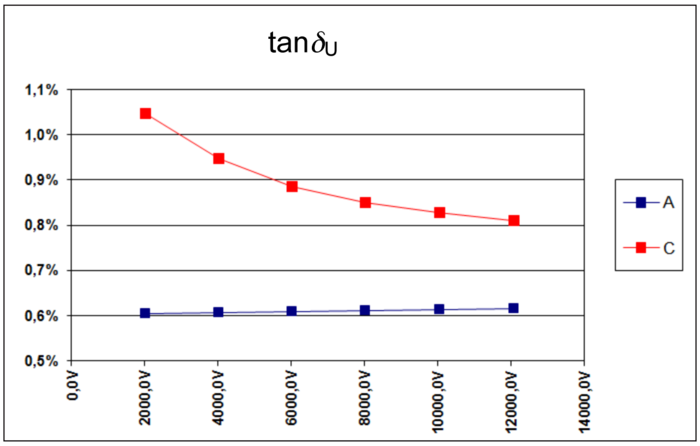


Figure 4.1.3.8: Dependence of tanδ with voltage:
A - healthy (RIP) bushing, C - bushing with test tap contact problem

Poor contact inside of the bushing can also be detected with FDS measurement as is shown in Figure 4.1.3.9.

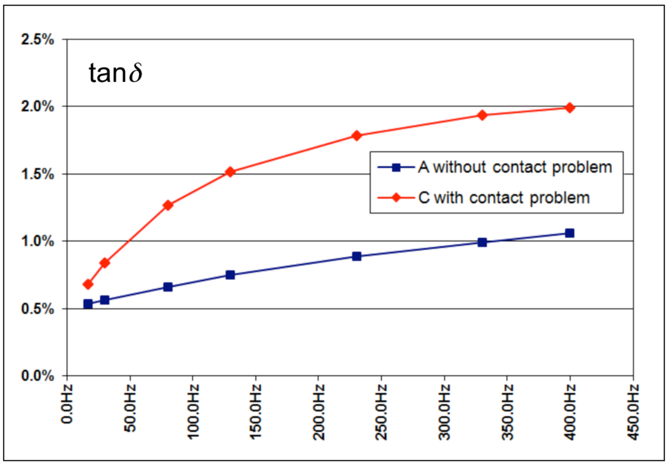


Figure 4.1.3.9: FDS measurement results in 15-400 Hz
frequency range with and without contact problem

The FDS measurements shown in figure 4.1.3.9 were made on two RBP bushings. The bushing of phase C (red curve) had a contact problem between the innermost grading layer and conductor tube. This resulted in a high dissipation factor value at higher frequencies. It can be suspected than poor test tap contact will show a similar FDS measurement pattern.

Capacitance and tanδ measurement instability also indicates contact problems, and this often means test tap problems. The subsequent inability to measure these quantities means a disconnection inside of the bushing and an increase in the severity of the problem. Bushings with a test tap contact problem should be replaced without delay because of a possible temperature increase and gas generation in the oil (OIP). If this problem is allowed to persist, it can penetrate deeply into the condenser body making a puncture that grows until breakdown/collapse, Figure 4.1.3.10. There are various reasons for a bushing test tap contact problem such as bushing mechanical overloading that can cause mechanical movement and/or loosening of contact pressure (Figure 4.1.1.2), high impulse current – refer to VFT problems below, [4.1.3.4], improper soldering (cold joint, Figure 4.1.3.11), up to too much fragile test tap solution.

Figure 4.1.3.10: Test tap problem that penetrated deeply into the RIP body possibly caused by VFT (left core cut view, right: damaged test tap)

The test tap cover can be damaged or installed incorrectly resulting in an ungrounded or improperly grounded tap. Even a test tap cover that is installed correctly can be a problem if the cover's contact spring has been damaged.

An ungrounded test tap may jeopardize the bushing in a relatively short time. VFT problems regarding the test tap can appear if the test tap is earthed through a relatively large inductance. Large di/dt can cause a high voltage which will compromise the test tap’s insulation.

Figure 4.1.3.11: Improper soldering of the test tap contact (cold joint)

The test tap itself is isolated by a sealing system between the bushing interior and the tap, and between the tap and the bushing's surroundings. A poor sealing system can lead to moisture ingress into the tap and bushing interior, or an oil leak. Severe corrosion inside the tap due to moisture may cause improper bushing grounding, Figure 4.1.3.12. Today, it seems that test tap problem frequency is on the rise, probably because of more frequent usage for periodic (off-line) bushing diagnostic measurements and especially because of the increased application of continuous (on-line) condition monitoring, refer to section 5.2.

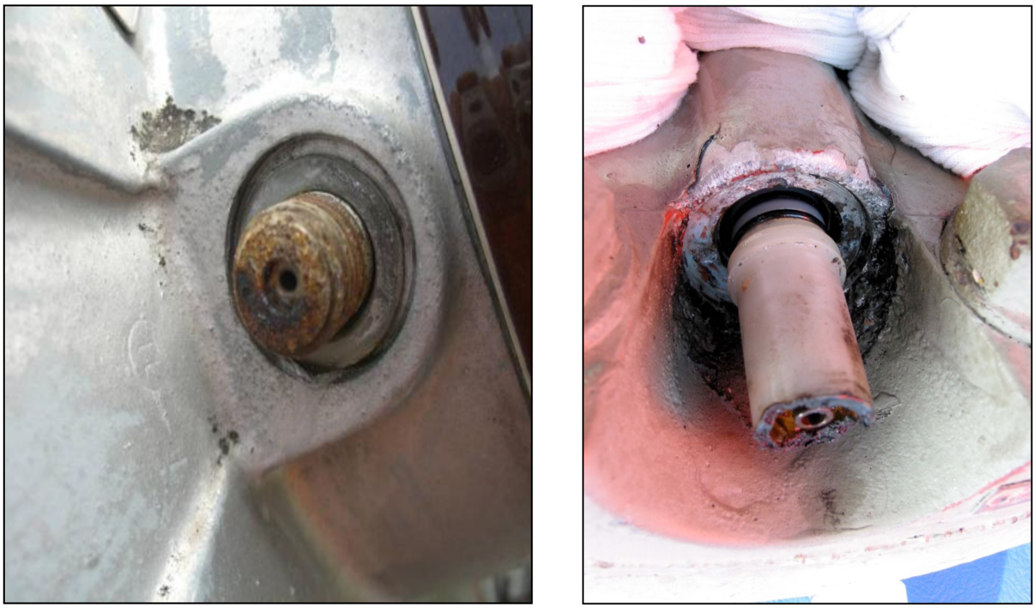


Figure 4.1.3.12: Left: corroded test tap caused by poor sealing, right: damaged test tap

Test tap can be affected by vibrations, so internal connection to the condenser core which relies on spring force is not recommended for reactor bushings, [4.1.3.12].

Bushing end shield problems

On-site problems with oil-end shields can be divided into assembly and electrical (breakdown) problems.

End shield assembly problems occur because of poor fixation design, poor on-site installation or both. Under the influence of mechanical forces and vibration in service, the end shield can fall off the bushing. Normally it will stop somewhere below the bushing's lower end, hung-up on the lead. Possible consequences are intensive PD activity, low energy arcing in oil or even breakdown, Figure 4.1.3.13.

This can be detected thorough DGA analysis (PD or low energy arcing) or Buchholz relay first stage activation. Electrical off-line periodic diagnostic methods would not indicate any changes to the previous measurement with the exception of a small (often insignificant) bushing capacitance change. It can be assumed that on-site PD measurement or AE-PD location will detect the problem.

Figure 4.1.3.13: 245 kV bushing end shield fallen down (left), low energy arc traces on the shield (right)

End shield electrical problems results in PD or breakdown but for completely different reasons compared to assembly issue. An interesting problem of this kind is related to an end shield electrode covered with a thick (approximately ten millimetres or more) cast resin layer, [4.1.3.5]. The visual appearance of the cases are practically the same at the end - breakdown in transformer, Figure 4.1.3.14. Bushing end shield breakdown happens during normal operation after approximately 10 years of service. Transformer on-line (continuous) monitoring revealed no signs of overvoltages, DGA rise or bushings capacitance change. The transformer oil quality was adequate to new oil. PD tests performed for research purposes on the end shields taken from service revealed that several shields are PD active - several hundreds of pC at service voltage. Such PD are harmful for cast resin insulation. A possible failure scenario is as follows: in cast resin insulation, PD often shows progressive behaviour – rising with voltage duration. It can be assumed that at the beginning, PD in the end shield was low and probably not triggered during bushing testing because of the lower electrical field stresses in the vicinity of the shield due to a very large bushing test tank. Low PD in the end shield cannot be detected during transformer testing because it is masked by numerous other PD sources (acceptable PD level so as background noise are much greater for transformers than for bushings [2.1], [4.1.3.6]).

It can be suggested that a bushing end shield with thick resin insulation coating should be tested in a similar configuration as is used in the transformers, or to put it another way, should be tested to ensure that a similar electric field is applied on the shield insulation as will exist in the energized transformer.

This failure scenario is very difficult to diagnose on site. The PD are encapsulated in the resin and because of that there are no traces of gasses in the oil. No electrical diagnostic method is sensitive enough to such behaviour except maybe PD on-site measurement (high sensitivity is required). It should be noted here that the expected PD frequencies inside the resin differ from PD frequencies in oil. Probably due to that regular on-site electrical or AE-PD (acoustic emission partial discharge) measurements won't detect this failure mode.

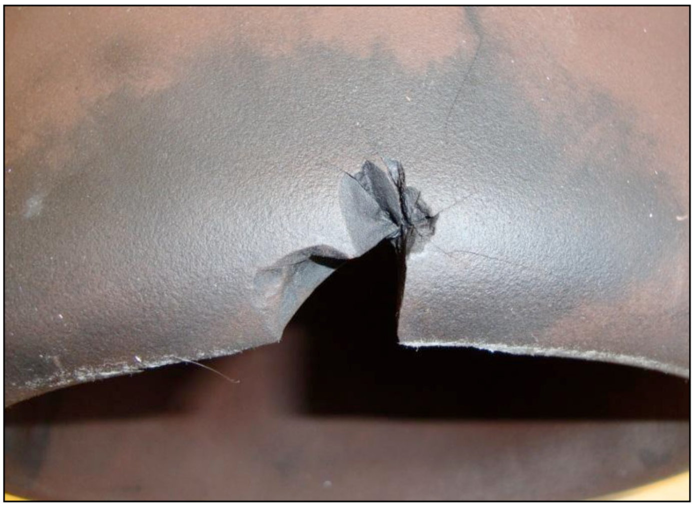


Figure 4.1.3.14: Two examples of similar cases showing end shield electrical problems: breakdown traces on 420 kV bushing end shield in turret (left), detail of end shield resin rupture after breakdown (right)

Very fast transient problems

It is known that HV equipment and thereby bushings connected to the power network through SF_6 switchyard (GIS) or switchyard equipped with vacuum type circuit breakers are exposed to very fast transients [4.1.3.7], [4.1.3.8], [4.1.3.9]. Bushings are severely stressed by these transients because they are the closest to the VFT source and the VFT wave travels along GIS practically without attenuation. The source of the VFT is circuit barker, specifically the disconnector operation, caused by arc ignition and/or reignition. Other events such as a breakdown in GIS, restrike/back flashover or arcing horns activation in the vicinity of the bushing can cause severe VFT. Mentioned phenomena are substation-specific, [4.1.3.9], and have been known for a long time but because of some new trends in power networks it seems that VFT appears more common than in the past. This is a consequence of the rising proportion of alternative energy generation which causes more frequent operation of circuit breakers and disconnectors, increasing usage of SF_6 switchgear and vacuum type circuit breakers. The rise time of such VFT extends deeply into the nanosecond range, down to and even lower than 20 ns, and according to some references [4.1.3.10] down to 2 ns.

Generally, bushings are resistant to such events. Their cylindrical shape results in a capacitive voltage distribution being established very quickly. In spite of this, VFT can cause internal bushing resonances. Very high steepness of the voltage causes very high current impulse. These current impulses, if repeated frequently, can damage some parts of bushing. Vulnerable parts are the connection to the first and last foil of C_1, the overlapping area of the electric field grading foils (refer to chapter 2) and perhaps the most endangered is the test tap. The test tap can be considered as an inhomogeneous point, compared to the almost ideal coaxial arrangement of the grading foils (the axial distance between adjacent foil ends is only a few centimetres) which have good high frequency properties. Consequently, due to coaxial arrangement bushings have very low damping characteristic to traveling waves. To the contrary, the test tap can be considered as a "serial inductive component", especially if the ground connection is not very short. VFT can produce resonances and overvoltages at this inductance, which can lead to damage of the tap insulation. It should be noted here that currents passing through the test tap when the bushing is exposed to a VFT can reach an amplitude of several kA.

For example, according to [4.1.3.11], simplified calculations of the currents passing through the test tap of a 400 kV bushing with capacitance C_1 of 500 pF are shown below:

- Service voltage: 400 kV, 50 Hz: $I = U \cdot \omega \cdot C$ = (400 kV/√3) 2π×50 s^{-1}×500 pF ≅ 35 mA
- Switching impulse, standard front of 0,25 ms: amplitude 500 kV, $I = C \cdot dU/dt$ = 500 pF·500 kV/0,25 ms ≅ 1 A
- Lighting impulse, standard front of 1 μs: amplitude 500 kV, $I = C \cdot dU/dt$ = 500 pF·500 kV/1 ms ≅ 250 A
- Impulse VFT front of 20 ns: 500 kV, $I = C \cdot dU/dt$ = 500 pF·500 kV/20 ns ≅ 12,5 kA

Note: Impulse voltage amplitude 500 kV is just an example, for 400 kV it corresponds to approximately 1,5 p.u.

Despite the very short duration of the current caused by VFT, it can result in damage of the test tap contact if it occurs frequently. The current from the VFT event itself causes only a small amount of damage but subsequent normal service current (up to approximately several tens of mA) will then enlarge the damage, as shown in the previous Figure 4.1.3.10.

Figure 4.1.3.15: Cavity in RIP possibly caused by VFT (enlarged)

It was reported on WG meetings that the overlap of the grading foil (especialy the size and the conductive connection of the foil ends) plays a role in VFT behaviour of the bushing, Figure 4.1.3.15.

According to [4.1.3.7] and [4.1.3.10], in normal cases, VFT amplitude does not reach a value above 2,5 p.u. or so (2,5-times the service voltage peak value). Bushing (oil-SF_6, SF_6-SF_6) of standard design fulfil this requirement. In the past decade, the understanding of bushing-related VFT problems has significantly increased, leading to improvements in design and test-capability for higher VFT amplitude, but the reasons for such requests is not completely clear.

Degradation of the condenser core caused by VFT can be detected by dielectric response measurements and DGA (for OIP bushing type), [4.3.1].

4.1.4. Chemical, pollutant and environmental

Traditionally, moisture is one of the most dangerous types of pollutant, especially for the OIP bushing insulation system. Moisture has multiple undesirable effects in OIP bushings. The most prominent issues are:

- Reduction of breakdown voltage;
- Dielectric loss increase especially at higher temperatures resulting in thermal instability (thermal runaway), refer to section 5.2.2.2;
- Accelerated ageing, i.e. life expectancy decrease.

The relative life expectancy of the OIP insulation system as a function of the paper's moisture content, according to various criteria and authors, [4.1.3.2], [4.1.3.11], is shown in Table 4.1.4.1. All show a very significant influence. For criteria 1 and [4.1.3.11], when moisture increases from 0,41 to 1%, the relative life expectancy is reduced approximately four times. Conversely, reducing the moisture content from 0,41 to 0,11% will extend life expectancy approximately 3,5 times.

Table 4.1.4.1: Relative life expectancy of OIP insulation system according to various criteria and authors

	Relative life expectancy, p.u.			
Humidity in paper (%)	Criteria 1	Criteria 2	Criteria 3	[4.1.3.11]
0,11	3,5	4,6	4,1	-
0,41	1,0	1,0	1,0	1,0
0,70	0,48	0,26	0,35	0,45
1,0	0,27	0,042	0,13	0,26
1,5	0,18	-	0,0047	0,15

According to [4.1.3.2]:
Criteria 1: doubled initial tanδ value
Criteria 2: tan$\delta = 5 \times 10^{-2}$ at 120 °C
Criteria 3: tan$\delta = 10 \times 10^{-2}$ at 120 °C

Moisture also penetrate into RBP and RIP bodies that are exposed to air, refer to chapter 6, and into composite upper housings because of cracks or improper shed moulding.

Poor sealing (moisture ingress)
The main reason for moisture ingress is poor sealing of any part of the bushing, caused by thermal (gasket ageing) and mechanical over-stresses (rigid connections, seismic disturbances, etc.) cracks in aluminium castings and loss of compression force (for compression type OIP bushing). Bushing overfilled with oil may also damage the bushing's sealing system. According to widely held beliefs, this failure mode is one of the most abundant ones, but our survey data (see Figure 3.4.1.10.) revealed only 8 % of bushing failure are related to oil leak and moisture ingress. The true number is probably a bit higher because some other listed causes may be also related to this issue. Moisture ingress can be slow or fast. Slow moisture ingress can be detected through increased tanδ measurement results, especially if the measurements are performed at elevated temperatures (refer to section 5.2.2.2). Fast moisture ingress can happen, because of a poor seal, when the bushing experiences a sudden temperature drop. This causes water to be sucked in from the outside, often resulting in axial breakdown of the bushing's lower part, Figure 4.1.4.1. According to [4.1.3.2], about a year before failure, tanδ shows a slight increase from about 0,4 to 0,5 % with no capacitance change. No arc traces were found on the lower part of condenser body.

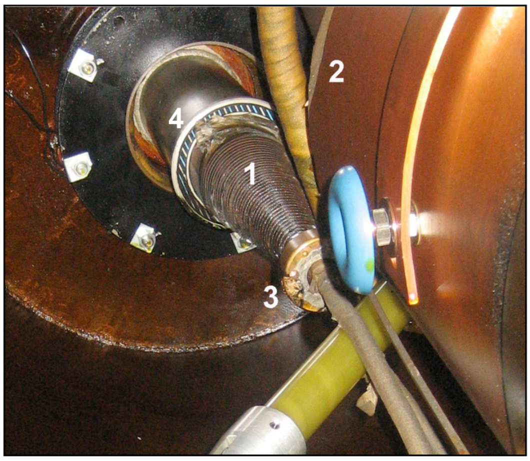


Figure 4.1.4.1: Compression tye OIP bushing failure probably caused by fast moisture ingress after 40 years of service (view inside of the transformer tank, looking upwards:1- bushing lower part with bursted lower envelope missing, 2- broken OLTC cylinder (consequence of hydro-dynamic shock), 3 - arc traces on the bottom metal part, 4 – arc traces at the bushing's current transformer extension

Moisture ingress can occur on any bushing types but OIP (especially compression type) seems to be the most vulnerable in seismically active regions. A clasp can be used as a useful on-site measure for OIP compression type bushings, [4.1.1.2]

Moisturising from inside

When discussing moisture in OIP bushings it is considered that moisture penetrates from outside of the bushing through a poor sealing system or other porous parts but, another way of OIP bushing moisturising exists, [2.1.4], [4.2], [4.3], [4.4]. Water in an OIP insulation system can be in three basic stages:

- Dissolved water in oil. Each mineral oil has ability to absorb certain small amount of water. The ability to absorb the water rises with temperature and oil ageing. Only this water (moisture content) can be measured from a standard oil sample.
- Free water (droplets, mist, …). This appears when the oil's water-solubility is exceeded or the bushing sucks in the free water from outside of the bushing. Water in this form drastically lowers the dielectric strength of the OIP system.
- Chemically-bonded water. This is water incorporated into the chemical structure of the oil. In certain circumstances, under slightly elevated temperature (but still normal operational temperature according to [4.1.4.1]) this water can be released from chemical structure and moisturise OIP system from inside.

The visual appearance of the bushing failure due to released water is lower envelope destruction by axial flashover in between the condenser body and the lower envelope. Reports indicate the development of waxy deposits on the inner side of the lower envelope. It happens on relatively new bushings, approximately 3 to 15 years old. Failures are more often found on transformers operating at higher temperatures. Failure cause was insulating oil with a high level of aromatic hydrocarbons in its chemical structure (about 18 %). During bushing service water is released from the oil and moisturising the oil and paper in the condenser body. This results in PD in the lower part of the bushing and finally breakdown. It is reported that this type of failure can effectively be prevented by measurement of C_2 and tanδ_2 – they may represent the oil quality depending on the particular bushing construction.

Corrosive sulphur and copper mobility in OIP bushings

In the 1990's, it became apparent that compounds which contained sulphur were present in some transformer oils which over time would decompose at elevated temperature releasing the sulphur [4.1.4.2], [4.1.4.3] The released sulphur was then able to react with copper and form harmful copper sulphide. The industry addressed this by upgrading the way oils are tested for the presence of sulphur, but not before numerous transformers were lost. In the early 2000's, it became clear that this same issue was occurring in bushings containing copper. The aforementioned compounds would break releasing sulphur that reacted with the copper to form copper sulphide settling on the insulation of the bushing resulting in partial discharge that, in some cases, damage the condenser enough to compromise its performance. The increased losses in the condenser would result in elevated power factor (or tanδ) and could eventually result in a complete breakdown. The evidence of copper sulphide can be found as a blackening of the copper components and an odd iridescent green discoloration of the condenser paper, Figure 4.1.4.2, [4.1.4.3].

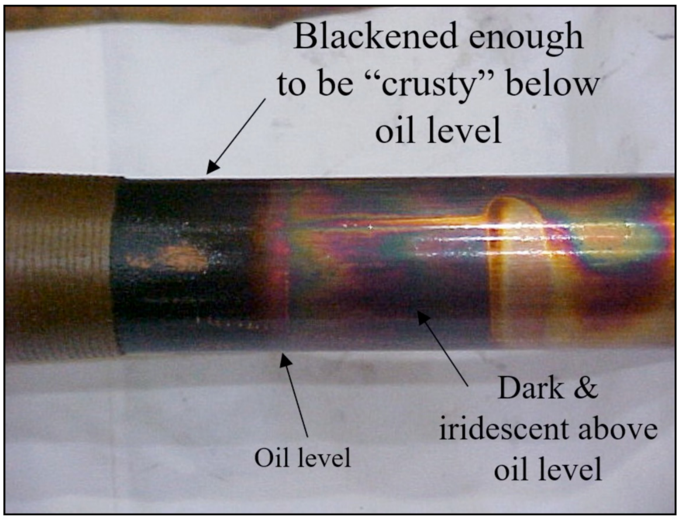


Figure 4.1.4.2: Evidence of copper sulphide: blackening of the bushing copper central conductor, [4.1.4.3]

Laboratory testing can confirm the presence of copper sulphide in the paper.

The copper mobility phenomenon differs from corrosive sulphur, but they are similar in a way. Both are related to bushings with copper conductors. Under certain conditions, copper chemical compounds can be dissolved in bushing oil and transferred and deposited onto the paper in a highly stressed areas caused PD, treeing, increased losses and finally breakdown, [1.1.3], [4.1.4.4], [4.1.4.5].

Small animal problems

Small animal problems can be considered as a specific kind of pollution. The most effective prevention method is visual inspection of the bushings together with the installation of protective elements. Knowledge of the behaviour and the presence of these animals in the specific environments is also valuable.

Generally, this is mainly a distribution voltage bushing problem. Small animals like birds, cats, martens, weasels, dormice, bats, rats, etc., can compromise air clearances causing short circuit between phases or to earth that can harm bushings with an electric arc or transformers through short-circuit forces. These events increase at colder times of the year. Additional insulation, insulating caps, protective barriers, protective cages, etc. are used to prevent electrical contact. The choice of the device depends upon utility practice and availability on the market.

It should be noted here that improper protection can increase the risk from small animals. For example, if a protective cage is used it should be mounted on the transformer in such a way that the smallest birds can't enter the cage. A trapped bird will flutter its wings trying to escape, greatly increasing the chance of a fault.

Note: Several decades ago this protection activity was called "protection of the transformer from small animals". Today it is better to use the term "protection of small animals from a transformer". This kind of bushing failure can be considered as a pollution problem in the sense that transformers pollute the environment.

Pollutant and environmental

Pollution of the bushing's upper envelope (upper housing) may jeopardize its creepage property resulting in flashover. Flashover along a bushing is hazardous to the integrity of the bushing, more so for a porcelain housing than for silicone (composite). Pollution is more hazardous in wet conditions (especially at the beginning of wet). The most effective prevention method is visual inspection of the bushings.

Deposits on the upper envelope can affect tanδ, (it can rise or decrease, [5.2.2.1], [5.2.2.2]).

- Usually, silicon sheds are more resistant to ordinary pollution than porcelain. That means that porcelain sheds should be cleaned more frequently than silicone. For improving porcelain surface hydrophobicity, appropriate coatings (grease) may be used.
- Shed extensions (available on the market) made of adequate material can be used as a temporary remedial action to increase creepage length.
- One environmental condition that may affect the condition of a bushing upper envelope is abrasion caused by strong wind-carried salt or sand. Reports indicate that porcelain is more resistant to the abrasion from severe salt spray while silicone is much more susceptible to this kind of damage.
- In very wet climates part of the silicon upper envelope can experience growth of certain green organic deposits on its surface, Figure 4.1.4.3, [2.1.2]. Other than unsightly appearance, no reports of failure are related to this phenomenon. This organic deposit affects the bushing's tanδ especially in LF measurement.
- Silicon sheds can be subjected to various animal attacks like rodents, birds and, as recently reported monkeys (in some countries), [3.2.8]. This phenomenon is known as a storage problem, refer to chapter 6. Some of them may attack silicone sheds even in service, Figure 4.1.4.4. In South East Asia, it is a serious problem. It is not understood why the animals attack silicon sheds. It doesn't have any nutritional value for them at all. Development of silicone sheds resistant to this attack is suggested.
- Reports indicate that a bushing's upper envelope is normally more resistant to evenly distributed deposits along the surface compared to partly distributed deposits (salt, sand, snow, dirt, etc.). This means that if certain obstacle (walls, roof, etc.) is intentionally or unintentionally used to prevent forming deposits on the bushing's surface, the whole bushing upper envelope length should be protected. Deposits distributed only on a part of the bushing may results in a flashover.

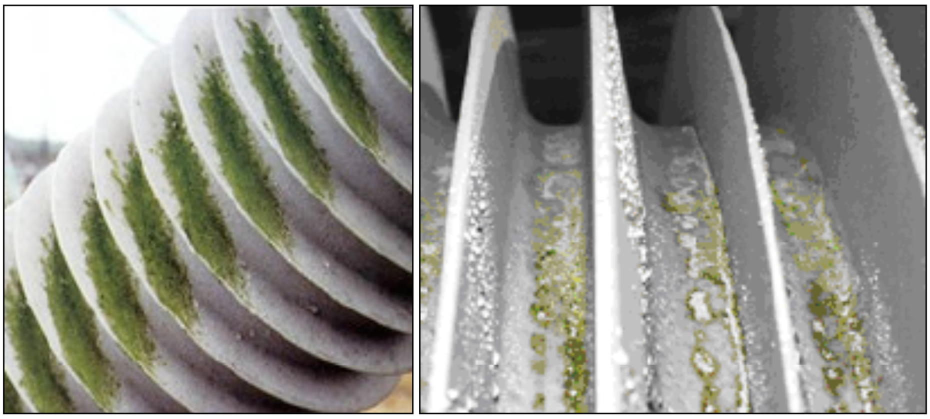


Figure 4.1.4.3: Green organic deposits on silicone sheds [2.1.2]

Figure 4.1.4.4: In-service bushing's silicon sheds attacked by monkeys [3.2.8]

4.2. Reflections on bushing diagnostics

On-site bushing condition diagnostic methods (periodic and continuous) have different diagnostic abilities to detect the development of certain failure mechanisms. This diagnostic ability or effectiveness of each method is listed in Table 4.2.1.

Table 4.2.1: Diagnostic method effectiveness for certain failure mechanisms

Failure mechanisms	Periodic (off-line) diagnostic methods and effectiveness	Continuous (on-line) diagnostic methods and effectiveness
Mechanical		
Seismic disturbance	VI (H to M)	Oil pressure (H)
Vandalism	VI (M to L))	Oil pressure (H to M), *C* (L)
Rigid connection to bushing	VI (H), tanδ (M), *C* (L)	*C* (M) tanδ (L), Oil press. (M to L)
Electrodynamic forces on bushing transformer part	VI (M)	-
Thermal		
Gas bubble evolution	PD (M), AE (H to M)	PD (H to M), AE (H to M)
Current path and contacts	IR (H), VI (M) tanδ (M to L), WR (L)	IR (H), *C* (M), tanδ (M to L),
Electric and dielectric		
Core cracking or delamination	*C* (H), PD (M), AE (H to M), tanδ (L)	*C* (H), PD (H to M), AE (H to M)
Electrode ends problems	tanδ (H to M), PD (M), AE (M)	tanδ (M), PD, AE (H to M)
Zig Zag condenser bushings	tanδ (H to M), PD (M), AE (M)	tanδ (M), PD (H to M), AE (M)
Test tap problems	tanδ (H to M), *C* (H to M), VI (M)	tanδ (M), *C* (H)
Bushing end shield problems	PD (M to L), AE (H to M)	PD (M), AE (H to M)
VFT problems	PD, AE (M), tanδ (L), *C* (L), DGA (M)	PD (M) AE (H to M), *C* (H to M)
Chemical, pollutant and environmental		
Poor sealing (moisture ingress)	tanδ (H), VI (L)	tanδ (M), Oil pressure (H)
Internal moisture generation	tanδ (L), tanδ_2 (H to M)	tanδ (L), PD (L) AE (L),
Corrosive sulphur in OIP bushings	Oil properties (M)	PD (L), AE (L)
Small animal problems	VI (H)	-
Pollutant and environmental	VI (H to M), tanδ (M)	CC (H to M)

Diagnostic effectiveness symbols:

- H – high: method is sensitive to the related phenomena
- M – medium: method is more or less sensitive to the related phenomena,
- L – low: results are useful but often inconclusive, other methods should be used to prove condition status

Diagnostic methods symbols:

- C and tanδ is used for bushing HV capacitance C_1 and related tanδ_1 (or PF). C_2 and related tanδ_2 are used for parameters between tap and flange
- VI: Visual inspection
- IR: Infrared scanning
- PD: Partial discharge measurement
- AE: PD qualitative registration and location by using of acoustic emission methods
- CC: creepage current
- DGA: dissolved gas analysis: only for OIP bushings
- Oil properties; Oil pressure: only for OIP bushings

Notes:
- Diagnostic effectiveness ranking is based on actual state of art is subject to change with future improvements to the diagnostic methods.
- Polarisation spectrum methods (PDC, FDS, RVM and their combinations) often yield promising results. Indicative limits for 15 Hz and 400 Hz are given in table 5.2.2.2.4. and in section 5.2.3.
- Visual inspection is effective only if the disturbance is visible and already apparent.
- C, tanδ measurements incorporate many modern approaches (voltage and frequency dependence, temperature correction, etc.).

4.3. Bushing life expectancy

It is very difficult to find exact and objective information about the life expectancy of the three bushings main insulation types (RBP, OIP and RIP). Life expectancy is clearly understandable for technical equipment not requiring maintenance or repair (no maintenance, no condition diagnosis). To the contrary, bushings are always subject to a certain level of maintenance and this influences life expectancy.

As usual, equipment load plays significant role in bushing ageing, so it is expected that reactor bushings and GSU transformers bushings have faster degradation of inner insulation system, [4.3.1].

A consensus exists that RBP bushings, because of inherent PD, have a lower life expectancy than the other two bushing types (PD cannot be improved by maintenance and it is still difficult to measure PD on site). According to [2.1.4], based on the research performed on almost one hundred RBP 123 kV bushings in a transmission network, it is revealed that the number of bushings in suspicious or bad condition rises significantly after 30 years of service. Figure 4.3.1, [4.1.3.2], supports this showing a RBP 245 kV bushing failure after approximately 30 years of service.

Figure 4.3.1: Exploded oil part of 30 years old, 245 kV, RBP bushing

Breakdown of this bushing was radial through the condenser body, probably as a consequence of thermal breakdown caused by increased dielectric losses. PD in the condenser body may play a significant role in the event.

For the OIP bushing type no such consensus about life expectancy exists. Opinions vary about bushing life expectancy: from about the same as a transformer, to less than the transformer's life expectancy in severe thermal conditions (climate, loading, etc.).

It is worthwhile to conclude here that bushing condition diagnostics, periodic and especially continuous, play an important role in their life expectancy, and especially in preventing bushing terminal failures and their associated costs.

5. Bushing diagnostics and monitoring

The purpose of bushing diagnostics and monitoring is to estimate the bushing's condition based on the measurement results (tests) or inspection. Measurements can be performed in two basic ways: periodic or continuous:

- Periodic or off-line bushing tests are performed on energised or de-energised transformers depending on the particular diagnostic methods.
- Continuous or on-line bushing tests (monitoring) are automatically performed on energised transformers with the extensive aid of computer.

The availability of the diagnostic methods for periodic and continuous application is detailed in Table 5.1.

Table 5.1: Availability of bushing diagnostic methods to periodic and continuous application, current state of the art

Diagnostic methods	Periodic (off-line)	Continuous (on-line)
Visual inspection	Yes	Yes
Capacitance	Yes	Yes
tanδ or PF (50/60 Hz)	Yes	Yes
FDS, PDC, RVM and R_{ins}	Yes	No
Winding resistance	Yes	No
Infrared scanning	Yes	Yes
PD measurement	Yes[1)]	Yes[1)]
DGA	Yes	Yes [2)]
Moisture in oil	Yes	Yes [2)]
Creepage current	No	Yes
Oil pressure	No	Yes
Transients	No	Yes

1) Sensitivity to low PD detection in the bushings may be a problem
2) Methods appropriate for continuous application but rarely used for bushings primarily because of high costs.

The reference literature supports the use of and proves the worthiness of bushing diagnostics. In this chapter, according to author's opinion and experiences, a particular best practice is provided. Unfortunately, this approach results in a useful but somewhat complicated system especially for in-experienced readers. This is the reason why a simplified but effective system for bushing condition ranking, based on bushing capacitance and dielectric dissipation factor measurement results, is presented in annex 5, [5.1].

5.1. Bushing temperature definition

Bushing diagnostic parameters are temperature dependant, so, bushing temperature should always be measured and recorded [2.1], [2.2]. This isn't a problem for bushing laboratory testing because the bushing is in thermal equilibrium with the surroundings media. For on-site measurements, periodic (off-line) and especially continuous (on-line), it is difficult task to estimate bushing's insulation temperature and it is impossible to measure, because the temperature is not constant inside the insulation volume and it varies with time. For on-line measurement, an adequate bushing thermal model should be used. This is a complicated approach (bushings are cooled by two insulating media: surrounding air and transformer oil) and can't be used without very specific bushing parameters which are normally unknown to utilities.

For on-site off-line measurements, when the transformer is de-energised for at least a few hours, the change in transformer and bushing temperatures during measurement time can be neglected. There are two key bushing temperatures that should be measured:

- Bushing flange temperature (for bushings mounted on the top of the tank, this temperature is approximately equal to the top oil temperature). This temperature is the most important. Several bushing manufacturers refer to this temperature as the bushing temperature.
- The bushing's head temperature.

Note: Measuring the temperature along the sheds is uncertain, and it is not recommended.

In many cases, a significant temperature difference appears between the flange and head. In such cases, by using a longitudinal temperature model, the bushing's average temperature can be estimated according to (5.1.1), [2.1.4]:

$$\vartheta_{\mathrm{av}} = \frac{h_{\mathrm{o}}\vartheta_{\mathrm{f}} + 0{,}5h_{\mathrm{a}}\left(\vartheta_{\mathrm{f}} + \vartheta_{\mathrm{h}}\right)}{h_{\mathrm{o}} + h_{\mathrm{a}}} \tag{5.1.1}$$

Where:
ϑ_{av} – average bushing temperature,
ϑ_{f} – flange temperature (approximately equal to the top oil temperature or tank cover temperature),
ϑ_{h} – bushing head temperature,
h_{o} – part of condenser body length below the flange, including the flange height (this part of the condenser core is approximately at temperature equal to the transformer's top oil temperature)
h_{a} – part of condenser body length above the flange, can be approximated with upper envelope length (temperature varies from ϑ_{f} to ϑ_{h}).

Values h_{o} and h_{a} can be approximated from the bushing dimension data. For bushings without a current transformer extension (sleeve) approximately valid estimate is:

$$3h_{\mathrm{o}} = h_{\mathrm{a}} \tag{5.1.2}$$

and the bushing temperature from (5.1.1) is:

$$\vartheta_{\mathrm{av}} = 0{,}63\vartheta_{\mathrm{f}} + 0{,}37\vartheta_{\mathrm{h}} \tag{5.1.3}$$

Note: Current transformer extension length increases the ϑ_{f} multiplier and decreases the ϑ_{h} multiplier, but their sum is always 1 (p.u.). For IEEE standard bushing dimensions refer to [2.3].

Regardless the method to determine the on-site bushing average temperature, it is recommended that three on-site temperatures should be measured and recorded: bushing flange and head temperatures and ambient air temperature.

The bushing's temperature changes with time so these measurements should be performed immediately before bushing parameter measurements. An average value of the relevant temperatures (before and after measurement) may be used also.

5.2. Bushing off-line (periodic) diagnostic methods

5.2.1. Visual inspection

Despite common opinion, visual inspection is a sophisticated diagnostic tool and should be carried out by qualified personnel. Bushing visual inspection can be performed during service (maintaining a safe distance) or during an outage. Always keep in mind the relevant safety recommendations and rules, and wear personal protective devices (gloves, eyeglasses, helmet, protective coat or raincoat, boots, etc.). Binoculars, camera and a flashlight are very useful. The aim of visual inspections is to check the physical condition of the bushing, preventing a possible emerging problem in its early stage. During the visual inspection at site, the following aspects can be inspected. The background to these aspects are also provided. The list is a summary and it is not meant to be an exhaustive list. Some aspects are not appropriate for certain types of bushings.

- **General condition of the bushing** (surface condition, position, rating plate presence and readability, porcelain condition and damages, etc.).
- **Condition of the sheds** (pollution, hydrophobicity – see note below, damaged or eroded sheds, if silicone sheds losing their original shape may be a sign of oil leaking somewhere above, etc.).
- **Oil level** (keeping in mind the actual loading and ambient temperature, leakage, etc.). If the oil level gauge is equipped with a floating ball, misreading happens occasionally because of oil absorption by the ball can cause it to sink.
- **Oil Colour** (via the gauge) Oil should be of light colour and transparent. Darkening of the oil and/or opacity (cloudy appearance) is a sign of ageing, excessive moisture or carbon particles.
- **Gasket condition** at the bushing head and flange and between transformer's tank/turret and flange. Look for oil leaks and moisture ingress.
- **Cement condition** between the upper porcelain envelope and the head or flange. Look for oil leaks and mechanical overload.
- **Position of porcelain** towards flange and head. Check axial pressure.
- **Mechanical condition of connections** to the switchyard (flexibility, connection should not be too rigid, prevention of mechanical overloading caused by thermal dilatation).
- **Upper contact condition** (overheating traces appearing as a colour change, mechanical tightness).
- **Plated current connections condition** (silver plated, tinned, corrosion, changing of colour, etc.).
- **Condition and position of corona rings and arcing horns.**
- C**ondition of test tap and/or voltage tap** (leakage and/or moisture ingress, internal connection – often performed during diagnostic testing).
- **Grounding connection** between the bushing flange and transformer tank/cover/turret.

Most of these aspects can only be inspected when the bushing is de-energized. However, a few are performed when the bushing is energized. Binoculars and a camera are helpful, especially in the case of an energized transformer.

Bushing visual inspection can also be performed after a bushing failure as failure research. Generally, the same aspects as listed above should be inspected. For this inspection a magnifying lens, pincers, appropriate specimen containers (syringes, bottles, plastic bags, etc.) are often very useful. The way in which the spreading of bushing and its debris into switchyard occurred can help reveal which envelope exploded first, [1.1.3].

IR scanning can be considered as a specific visual inspection in the infrared spectrum but because of its importance and complexity, it is explained in section 5.2.5.

Note: The hydrophobicity of the bushing sheds surface is defined according to the hydrophobicity classification (HC), [5.2.1.1], from HC1 – best condition (water droplets are round and do not wet the surface), to HC7 – poor surface condition (droplets are not visible: surface is completely wet in the entire observed area). If no recommendation is provided, a hydrophobicity classification up to and including HC3 can be considered satisfactory. The bushing shed's hydrophobicity (especially porcelain) can be restored and improved by cleaning the sheds with the recommended solvent or by using a recommended coating. It is suggested that decision about sheds cleaning should be taken after hydrophobicity classification.

5.2.2. Bushing as a real condenser

At the current state of measurement technology, one of the most efficient techniques for bushing condition monitoring is based on capacitance C and the associated dielectric dissipation factor tanδ (or PF). It is possible to apply these tests to all types of condenser-type bushings equipped with a measuring tap, regardless of whether the transformer is in service or not. According to Figure 2.1., two capacitances of bushings can be measured, C_1 and C_2, and their associated dielectric dissipation factors, tanδ_1 and tanδ_2. C_1 is the high voltage capacitance measured between the HV connection and the measuring tap. C_2 is the capacitance between the measuring tap and the earthed flange and other earthed parts. Capacitance C_2 cannot be measured while the transformer is in service, while C_1 may be measured with the transformer in service or out of service. C_1 and tanδ_1 may be used for reliable diagnosis of the status of the bushing condenser body's insulation. An increase of C_1 indicates a breakdown of the bushing's elementary condensers and an increase of tanδ_1 indicates increased loss in the bushing's insulation system, which is often caused by moisture or ageing.

Capacitance C_2 and tanδ_2 of the test tap are less stable during service compared to C_1 and tanδ_1, and their diagnostic value significantly depends on the bushing and transformer design, [2.5]. That means the capacitance C_2 referred to as is the accidental capacitance which exists between the outer layer of the C_1 capacitor and any ground in the vicinity, such as the flange, turret, and current transformers. The tanδ_2 rarely can give some valuable diagnostic information, see Table 4.1.2.

Capacitance C_2 and tanδ_2 of the voltage tap, refer to Figure 2.1 diagnostically act in the same way as C_1 and tanδ_1 and can be used together for decision making but normally with no additional information.

It can be concluded that capacitance C_2 and tanδ_2 measurement results aren't very useful for bushing diagnosis.

From this point forward, the symbols C and tanδ refer to C_1 and tanδ_1.

At harmonic conditions, real condenser and their insulation losses, represented by tanδ, are described as:

$$i = \mathrm{j}\omega C u = \mathrm{j}\omega\varepsilon_0(\varepsilon_{\mathrm{r1}} - \mathrm{j}\varepsilon_{\mathrm{r2}})\frac{S}{d}u = i_R + \mathrm{j}i_C \quad (5.2.2.1)$$

$$\tan\delta = \frac{i_R}{i_C} = \frac{\varepsilon_{\mathrm{r2}}}{\varepsilon_{\mathrm{r1}}} = \frac{1}{\omega R_{\mathrm{e}} C} \quad (5.2.2.2)$$

$$\mathrm{PF} = \mathrm{Cos}\ \varphi = \frac{i_R}{i} \quad (5.2.3)$$

Where:
i – current through the capacitance C (geometry of the electrodes is generally defined by the electrode surface S and the distance between electrodes d)
u – voltage at the condenser C;
ω - angular frequency = $2\pi f$;
ε_0 – permittivity of free space (vacuum);
ε_r – relative permittivity of a material, as a result of electric polarization;
ε_{r1} – real part of the relative permittivity, represents capacitance;
ε_{r2} – imaginary part of relative permittivity, represents losses in capacitance;
i_R – active part of current i;
i_C – reactive part of current i;
R_e – equivalent resistance; represents losses in capacitance C;
PF – power factor (cosφ, sinδ)

Real (lossy) condenser phasor diagram and equivalent circuit are shown in Figure 5.2.2.1.

It is interesting to note that the tanδ measurement is much more sensitive to outside influences compared to the capacitance measurement because of the very small value of angle δ.
For tanδ = 0,5 %, angle δ is less than 0,3°. So, even a very small disturbance in δ (that can be caused with losses in the surrounding space, conductive losses, etc.) will significantly influences the results. For example, in the case of deposits on the upper or lower envelope's outer or inner surface, tanδ may reach even a negative value [5.2.2.1], [5.2.2.2]. For the same reasons, tanδ measurement should not be performed on a bushing placed in wooden transport package (dielectric losses in the package will be added to the bushing dielectric losses). The upper envelope surface should be dry and clean (recommended cleaners should be used if necessary). In wet weather conditions (rain, fog, snow, etc.), tanδ measurement is often erroneous especially in combination with deposits on the shed's surface. In this weather condition measurements should be avoided, or special measures should be undertaken. On-site measurements may be influenced by capacitive coupling to nearby energised lines. In this case, a special procedure should be followed (measurement in-phase and in anti-phase can eliminate this influence).

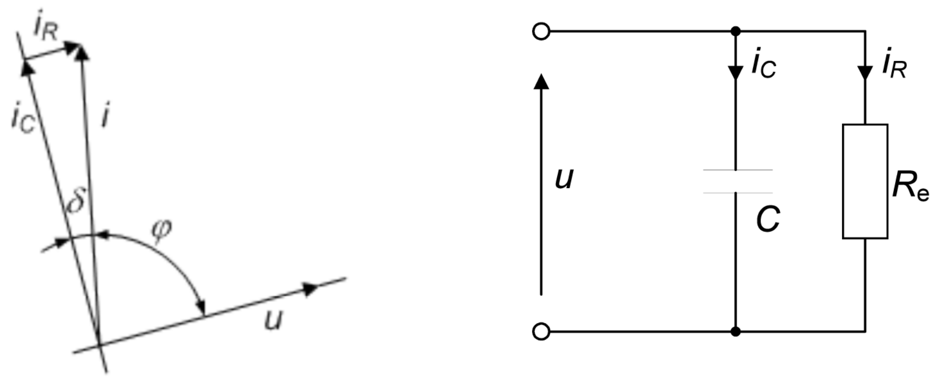


Figure 5.2.2.1: Real condenser phasor diagram (left) and its equivalent circuit (right) in harmonic condition

Normally, impurities in the condenser raise the tanδ value. The effect that some impurities may reduce tanδ value is intriguing, and slightly reduces tanδ's diagnostic effectiveness.

A short circuited elementary condenser increases the bushing capacitance. Reduction of the capacitance can only happen in the case of contact loss and can be easily recognized.

Bushing capacitance equivalent circuit on Figure 5.2.2.1. (left) cannot explain polarisation phenomena, see chapter 5.2.3. Resistance R_e represents dielectric losses (polarization and conductive) only in harmonic conditions.

It should be noted that tanδ and PF (cosφ, or sinδ) represent different terms, refer to Figure 5.2.2.1 (left), but for bushing diagnostic purposes both values are practically the same (tan$\delta \approx$ sinδ for a small angle δ; up to tanδ = 0,17 the differences are negligible).

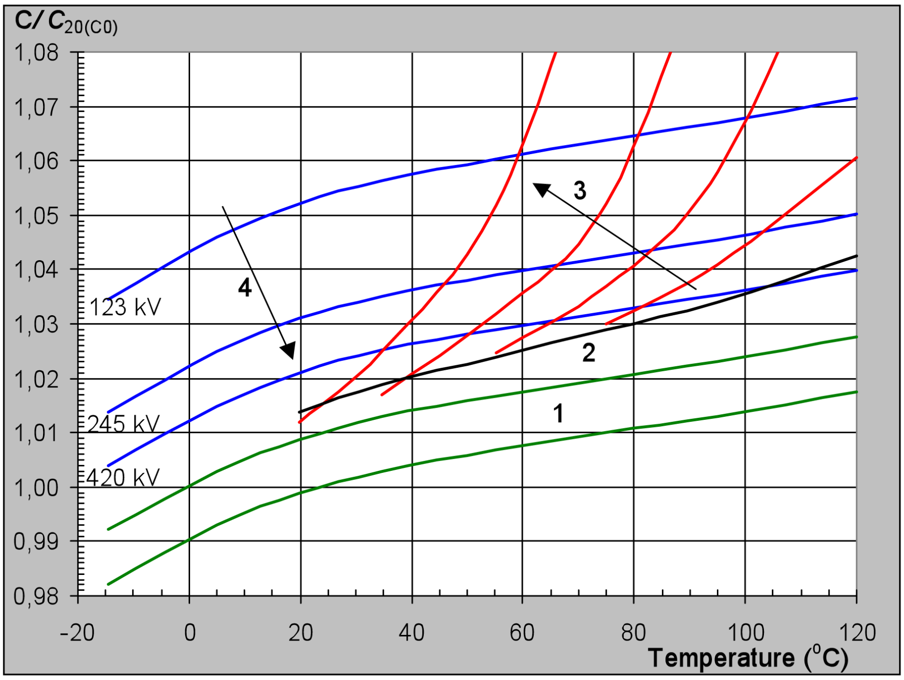
5.2.2.1. Capacitance

OIP and RIP bushing capacitance is a stable value during service and it is very sensitive to a bushing condenser core radial fault (short-circuited elementary condenser). To the contrary, bushing capacitance is less sensitive to a bushing axial fault (creepage breakdown along the upper or lower part of the condenser core). Fortunately, according to experience, radial bushing core faults occur much more often than axial. Bushing capacitance is temperature dependant (it increases with temperature) but much less than tanδ. For a healthy OIP bushings, this dependence is about $0{,}25\cdot10^{-3}$/°C for the temperature range from 5 °C to 95 °C, [4.1.3.2]. This dependence increases significantly with humidification and ageing. The bushing capacitance change ranking philosophy (compared to a new bushing) is shown in Figure 5.2.2.1.1. According to [2.1.2], for healthy RIP bushings, the capacitance temperature dependence is about $0{,}45\cdot10^{-3}$/°C for the temperature range from 25 °C to 100 °C.

It should be noted that humidification and ageing increases capacitance but only at higher temperatures. To the contrary, a short-circuited elementary condenser will increase the capacitance independent of temperature. This increase depends on the number of elementary condensers. The number of elementary condensers depends on the voltage, insulation type (OIP or RIP) and grading type (refer to Figure 2.2). A change in capacitance corresponding to short-circuited adjacent electrodes is relevant for decision-making. If the bushing capacitance change exceeds the expected change due to short-circuited adjacent electrodes, then the bushing should be replaced. It is suggested to list this value in the bushing's technical data or test protocol.

Bushing capacitance decreasing can bee consequence of poor test tap contact.

Note: For fine graded bushings with main and intermediate electrode technology the capacitance change that corresponds to short-circuited adjacent electrodes (refer to chapter 2 and Figure 2.2) is difficult to calculate and cannot be predicted as easily as for main electrode technology. In these cases, bushing manufacturers should define the allowable capacitance change for the bushing according to their experience. A similar situation exists for zig-zag bushing technology.



1 – Normal change of capacitance during the bushing's life (area between green lines)
2 – Criteria for qualitative assessment of ageing and water content (black line)
3 – Capacitance change caused by ageing and water content (arrow direction through red lines corresponds to an increase in ageing and water content)
4 – Capacitance change caused by a breakdown between the condenser layers (blue lines), (arrow is in the direction of increasing bushing rated voltage)

Figure 5.2.2.1.1: OIP bushing capacitance change ranking, $C/C_{20(C0)}$ represents the capacitance change compared to a new bushing (C0) at 20 °C

The approximate capacitance change corresponding to short-circuited adjacent electrodes, for fine graded bushings with main electrode technology is shown in Table 5.2.2.1.1, [2.1.4]

Table 5.2.2.1.1: Approximate capacitance change corresponding to short-circuited adjacent electrodes, for fine graded bushings with main electrode technology versus various system voltages U_m

U_m, kV	RIP capacitance change, %	OIP capacitance change, %
72,5	12	8,8
123	7,1	4,8
245	4,2	2,7
420	2,6	1,7
550	1,9	1,3
800	1,3	0,9

Note: The number of elementary condensers is not sufficient information to properly calculate the capacitance change if one condenser is broken, but it can be used as an approximation (if more accurate information is not available).

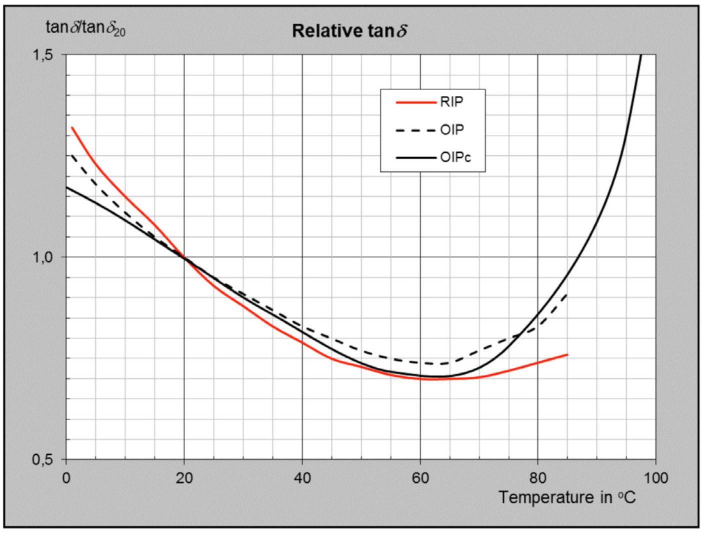
The capacitance of RBP bushings isn't stable in service because of oil penetration into the condenser body, refer to chapter 2 and section 4.1.3. This makes capacitance much less significant for RBP bushing condition estimation compared to OIP and RIP. The capacitance change caused by a short-circuited elementary condenser may easily be hidden by this effect. Limiting values for RBP capacitance change, based on experience, are presented in Table 5.2.2.1.2, [5.2.2.1.2].

Table 5.2.2.1.2: Limiting values for RBP bushing capacitance change

U_m, kV	RBP capacitance change, %
72,5	23
123	20
170	18
245	15
300	13
420	10

5.2.2.2. tanδ or PF (50/60 Hz)

Values of tanδ and PF are highly temperature dependant so bushing temperature should be recorded (refer to section 5.1.) and measurement results should be recalculated to a reference temperature according to the data given by the manufacturer. When this information is not available, Figure 5.2.2.2.1 can be used, [5.2.2.2.1], [4.1.3.2].



Note: OIPc is valid for OIP bushings when all of the bushing's insulation has a uniform temperature, [4.1.3.2]

Figure 5.2.2.2.1: Relative tanδ compared to tanδ at 20 °C for OIP and RIP

Bushing tanδ limiting and typical values are listed in Table 5.2.2.2.1, for the main bushing insulation types.

Table 5.2.2.2.1: Limiting values according to the standards and typical value range for tanδ and PF versus different bushing insulation types, at 50/60 Hz and 20 °C

Bushing insulation type	RBP	OIP	RIP
tanδ /% (new bushing), [2.1]	< 1,5	< 0,7	< 0,7
PF/% (new bushing), [2.2]	< 2	< 0,5	< 0,85
Typical value range, %	0,5 to 0,6	0,2 to 0,4	0,3 to 0,4

Bushing condition decision-making, based on tanδ measurement, depends on the bushing insulation type and generally has two approaches: based on reaching particular tanδ value or, more recently, reaching a particular relative tanδ change during service. A good and simple rule is that doubling of the initial tanδ value indicates a poor bushing condition, [5.2.2.2.2]. More specific decision-making criteria for OIP and RIP bushings, based on various sources and experiences, [5.2.2.2.3], [2.1.4] and [4.1.3.2] are listed in Table 5.2.2.2.2.

Table 5.2.2.2.2: OIP and RIP bushing condition decision making limits based on the relative tanδ change compared to the nameplate or initial value, at a reference temperature

	Bushing condition			
	Good	Moderate	Severe	Extreme
OIP tanδ relative change	up to 1,33	1,34 to 1,66	1,67 to 2	above 2
RIP tanδ relative change	up to 1,25	1,26 to 1,5	1,51 to 1,75	above 1,76

Good: Good or normal condition. All activities according to regular interval.
Moderate: Moderate deviation. Perform visual inspection, take additional measurement within 1 year. Continuous monitoring is suggested.
Severe: Severe deviation. Perform visual inspection, take additional measurement within 1 month. Continuous monitoring is suggested. Consider removal from service.
Extreme: Extreme deviation. Remove from service, or service may be prolonged for a short period (i.e. month) with continuous monitoring applied.

In the case of unexpectedly high dissipation/power factor values, the measurement should be repeated. The bushing should be cleaned prior to re-testing. Additionally, a collar which is connected to the guard circuit can be used to suppress the influence of the surface (creepage) current. Comparison of the results between phases should be used as an indication of erroneous measurements (the same tanδ increase in all three phases is highly unlikely).

For OIP bushings the tanδ change during service can be negative, [4.2], [4.4], [5.2.2.1], [5.2.2.2], refer to section 5.2.2. The relative decrease of tanδ to 0,8 times the initial value or less should be considered as significant and in need urgent action. If an OIP bushing shows such behaviour, the measurement of C_2 and its associated tanδ_2 is suggested. If results show an increase in the tanδ_2 value, bushing replacement is recommended. Increased tanδ_2 value is often followed with poor DGA results and increased moisture content in the bushing oil.

For RBP bushings tanδ limits are service voltage dependant, Table 5.2.2.2.3., [5.2.2.1.2]

Table 5.2.2.2.3: RBP tanδ limits at 20 °C

U_m, kV	RBP tanδ limit, %
72,5	2,3
123	2,0
170	1,8
245	1,5
300	1,3
420	1,0

Recent methodologies in tanδ diagnostics imply measurement with frequencies in the range of approximately 15 Hz to 400 Hz, [5.2.2.2.2], [5.2.2.2.3]. Indicative limits for these frequencies are given in Table 5.2.2.2.4. Generally, good condition is represented with small tanδ change in mentioned frequency range. High losses at lower frequencies can indicate high conductive losses by water or ageing by-products, high losses at higher frequencies can indicate inner contact problems at the measurement tap or the high voltage head connection or short circuits between grading layers which are not completely burned to a low resistive short circuit.

Table 5.2.2.2.4: Indicative tanδ limits at 15 Hz and 400 Hz

Bushing insulation type	RBP		OIP		RIP	
Frequency 15 Hz and 400 Hz	tanδ, %					
	New	Aged	New	Aged	New	Aged
	< 0,7	< 1,5	< 0,5	< 0,7	< 0,6	< 0,7

5.2.3. Dielectric response measurements on bushings

Two physical phenomena are responsible for the insulating material's basic dielectric properties: conduction (represented by charge flow caused by an electric field) and polarization (represented by charge orientation caused by an electric field). Dielectric spectrum measurement characterizes these phenomena. For condition assessment of the high voltage bushing's insulation, dielectric response (or dielectric spectrum) measurements plays an important role. Such measurements can be performed in the time domain - polarization and depolarization current measurement (PDC) as well as recovery voltage measurement (RVM), or in the frequency domain - frequency domain spectroscopy (FDS) also known as dielectric frequency response (DFR). According to [5.2.3.1] "all three measurement methods reflect the same fundamental polarization and conduction phenomena". So, in principal, the same information can be obtained from the results of these measurements, that leads to a simple, linear equivalent circuit for the description of the dielectric, shown in Figure 5.2.3.1:

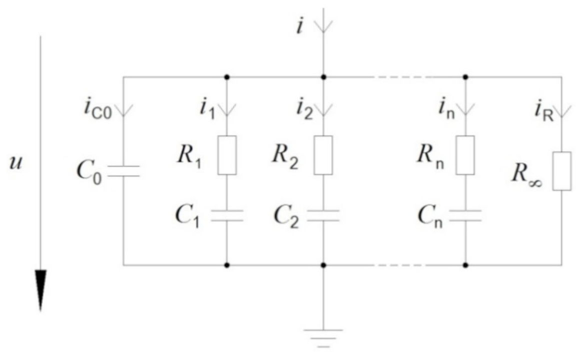


Figure 5.2.3.1: Linear dielectric equivalent circuit representation of a dielectric in the time and frequency domains [5.2.3.2]

This equivalent circuit consists of a capacity C_0 which contains information about the behaviour of the dielectric at higher frequencies, the insulation resistance R_∞ which describes the long time (low frequency) behaviour of the dielectric especially under DC-voltage, as well as several *R*-*C*-elements for to represent the polarization – especially boundary polarization inside the dielectric.

PDC as well as FDS measurements are the so-called three-wire measurements. This means, the measurement is applied between the high voltage electrode (centre conductor of the bushing) and the ground potential (transformer tank), while the test or voltage tap of the bushing is used to get the signal directly from the dielectric of the bushing. Using this method, it is assured that only the dielectric from the bushing is measured and the current, flowing to or through the transformer insulation is not contributing to the measurement signal, [5.2.3.1], [5.2.3.3]. For a bushing mounted on the transformer and-two wire measurement, the transformer's insulation parameters will mask the bushing's parameters. In this case (when two wire method is used), the measurement should be performed on the bushing after it is dismantled from the transformer.

It should be noted that regarding dielectric response measurements on bushings, the vast majority of data collecting so far is for OIP bushings.

Figure 5.2.3.2 shows how the PDC measurement is performed. A voltage step from zero to U is applied between the bushing HV terminal and ground, polarizing the dielectric. The polarization current flowing towards ground is tapped-off and measured at the measurement tap. After a certain polarization time t_p, the voltage source is shorted, and the dielectric is started to depolarize, so the depolarization current with negative polarity flowing from the inside of the dielectric to ground is measured. The polarization current contains information about the polarization and the insulation resistance. This method functions best, when the polarization time t_p is long enough, so that the polarization of the dielectric reaches a sufficiently charged state. This can take for several hours. It is also important that the depolarization time is long enough, to release all of the charge stored within the dielectric. Only than a reliable measurement result can be obtained.

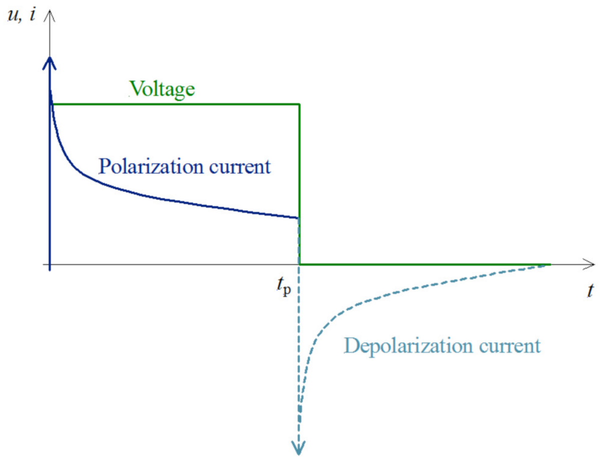


Figure 5.2.3.2: PDC sequence, voltage and current during PDC measurement

To draw a conclusion from the result of a PDC-measurement whether the bushing is in a good or bad condition, the curves must be analysed. For comparison, either curves from previous measurements or from bushings of the same type (age and condition) – so called fingerprints – can be used, or the measured curves can be compared with simulations where well-known material parameters are used. Simulation models are described in [5.2.3.2] and [5.2.3.6]. The case study shown further below, is an example of the evaluation of PDC and FDS results.

The FDS is performed by the application of a sinusoidal voltage with varying frequencies, over the range of about 1 mHz to 5 kHz, and measurement of capacitance and tanδ of the dielectric. The measurement results are plotted over the frequency range. In principle, the measurement results are not influenced by the size of the test object because only material parameters are considered. This allows the direct comparison of the measurement results between bushings of different sizes. The case study below shows some FDS results and shows the influence of temperature and water content.

For the evaluation of dielectric measurements, it is essential to consider the temperature of the insulation, because polarization and conduction are temperature dependent (a temperature increase results in a dielectric conductivity increase). Temperature may have a similar effect as ageing and moisture content. How the temperature of the dielectric measurement can be considered is shown in [5.2.3.4] or [5.2.3.5] and in the case study below. Influence of temperature on FDS results is shown on Figure 5.2.3.3. The measurements were performed on a 28 year-old service-aged 400 kV OIP bushing removed from a transformer. The average humidity content in the paper core (measured on paper samples) was 0,4 %. The FDS measurements shown were performed on the bushing at room temperature, 50 °C and 75 °C, [5.2.3.2].

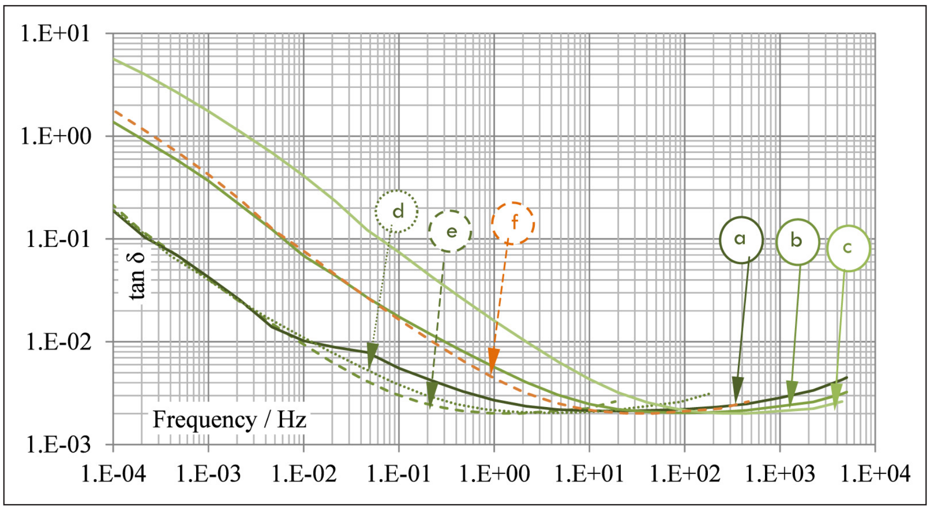


Figure 5.2.3.3: Results of a FDS measurement performed on a service-aged 400 kV OIP-bushing with 0.4 % water content in the paper at different temperatures: room temperature (a), 50 °C (b) and 75 °C (c), as well as curve "b" shifted to room temperature (d), and curve "c" shifted to room temperature (e) and to 50 °C (f), [5.2.3.2]

According to Figure 5.2.3.3, the FDS measurement curves at different temperatures can be transformed simply by shifting the curves along the frequency axis, to the left for a temperature decrease and to the right to temperature increase, [5.2.3.4]. This method can also be applied in the time domain. Figure 5.2.3.4 shows the results of PDC measurements on the bushing performed at different temperatures in comparison to the measurement of a severely aged 400 kV OIP bushing performed at room temperature. It can be seen that the increased temperature leads to a shift up of the long-time polarization current, while ageing effects lead to a vertical shift of the complete curve (short and long-time currents). It should be noted that the geometry of the bushing is influencing the PDC measurement result. Higher capacitances lead to higher polarization currents because the geometric parameters (distance and area) of the bushing's condenser core are influencing the capacitance and the conductance in the same way.

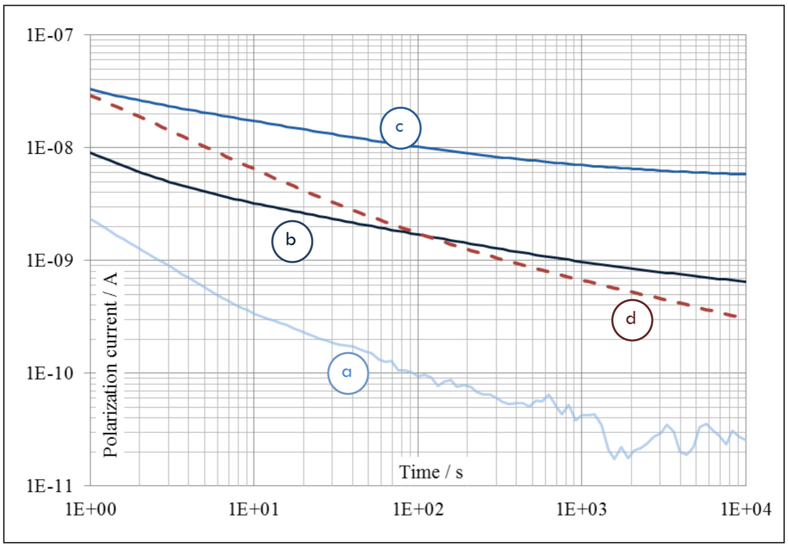


Figure 5.2.3.4: Results of a PDC measurement performed on a service-aged 400 kV OIP-bushing with 0.4 % water content at different temperatures, room temperature (a), 50 °C (b) and 75 °C (c), as well as a severely aged 400 kV OIP bushing performed at room temperature(d). [5.2.3.2]

Influence of varying amounts of water content on PDC and FDS measurements on bushings is shown in Figures 5.2.3.5 and 5.2.3.6. The curves were obtained by dielectric simulations based on material samples measured with different water contents.

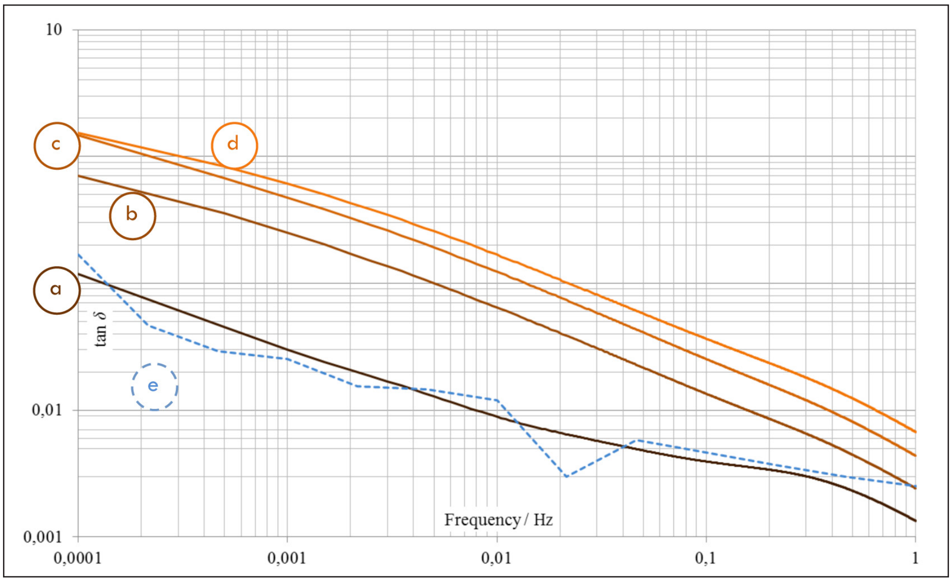


Figure 5.2.3.5: Results of FDS simulation on a 400 kV OIP-bushing at room temperature with 0.5 % water content (a), 1.5 % (b), 3,9 % (c) and 5 % (d), as well as an actual measurement on a 400 kV OIP bushing with 0.4 % water content performed at room temperature (e). [5.2.3.2]

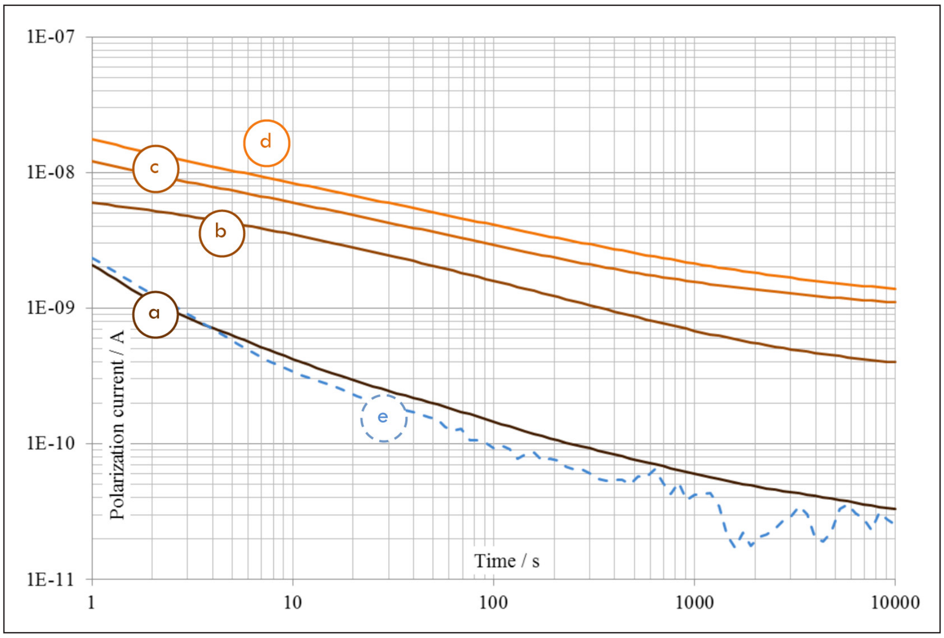


Figure 5.2.3.6: Results of PDC simulation on a 400 kV OIP-bushing at room temperature with 0.5 % water content (a), 1.5 % (b), 3,9 % (c) and 5 % (d), as well as an actual measurement on a 400 kV OIP bushing with 0.4 % water content performed at room temperature (e). [5.2.3.2]

These examples revealed that the FDS and PDC measurements curves should be evaluated based on comparison with measured fingerprint results or compared to simulated results, [5.2.3.2] and [5.2.3.6]. For PDC evaluation, the capacitance of the bushing must be considered. The bushing on which the above measurements were performed had a capacitance of 370 pF.

Based on the Polish research performed on more than 300 FDS measurements of OIP bushings in service, ranging in age from 12 to 41 years, revealed that 90 % of the values of moisture content in the paper are below 2,1 % [5.2.3.7].

An interesting example of FDS measurement is shown in Figure 5.2.3.7. Measurements are performed on the RIP core (bushing active part) before and after exposure to moisture in a climate-controlled chamber. Moisture can be detected in the low frequency range, similar to OIP bushings, refer to Figure 5.2.3.5.

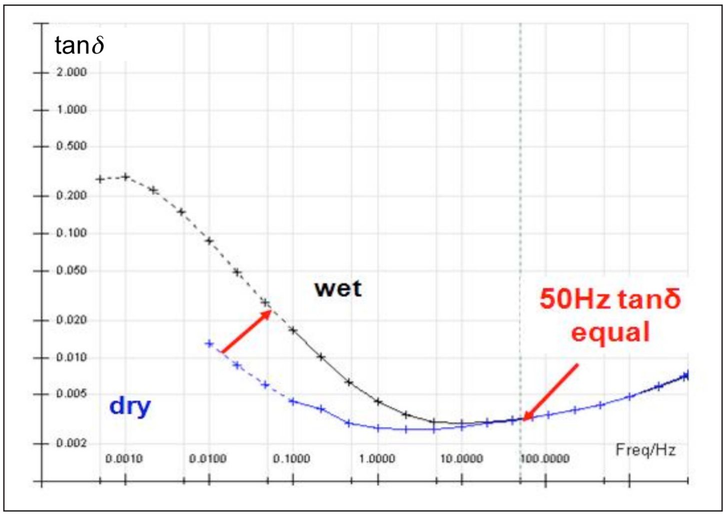


Figure 5.2.3.7: FDS measurement on RIP bushing core, before and after exposure to moisture

OIP bushing FDS results measured over a reduced frequency range of 15 to 400 Hz confirms that moisture can be detected at low frequencies, Figure 5.2.3.8.

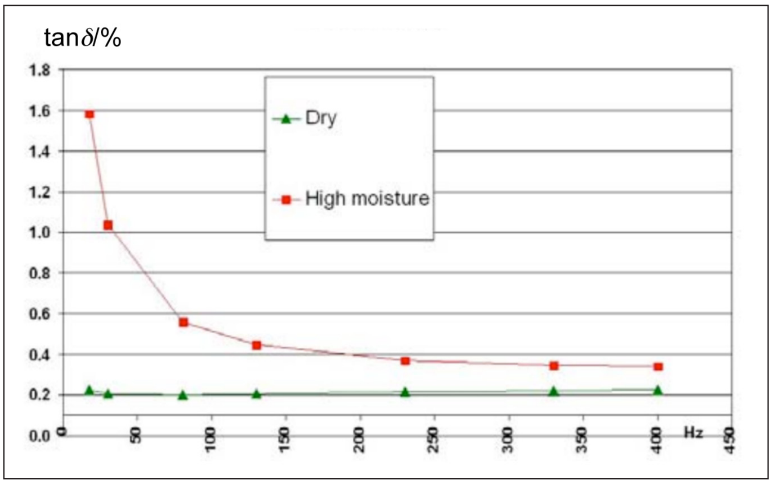


Figure 5.2.3.8: FDS measurement on a dry and wet OIP bushing over a frequency range of 15 to 400 Hz

The RVM measurement elementary sequence is based on charging (polarization) of the dielectric for a certain time, t_c. After the polarization phase, Figure 5.2.3.9, the dielectric is shorted-out for discharging time $t_d = t_c/2$. After the short is removed, the voltage recovering from the remaining charge stored inside the dielectric is measured, [5.2.3.8]. The voltage that recovers reaches a maximum value U_{max} at a certain time t_{peak} after removing the short. This elementary sequence is repeated for various tc in the range of fractions of a second up to 10000 seconds. Before each sequence, the dielectric should be shorted for a certain time to remove all residual charges. The RVM basic results represent the maximum recovery voltage U_{max} as a function of tc, $U_{max} = f(t_c)$. The maxima of this function can be expressed as a dominant time constant of the dielectric. This time constant is influenced by the temperature and condition of the dielectric (ageing and water content). The condition of the bushing's insulation can be analysed by comparing the measurement results to fingerprints.

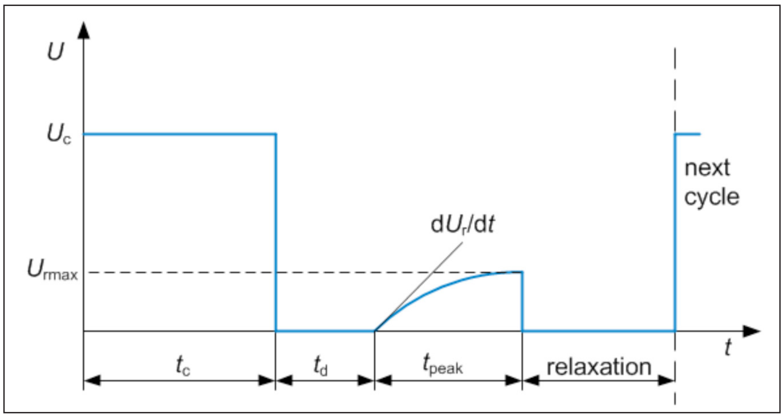


Figure 5.2.3.9: Recovery voltage measurement (RVM) sequence

Figure 5.2.3.10 shows the results of RVM measurements performed on different bushings at a common temperature. In principle, ageing and/or humidification of the dielectric leads to a shift of the dominant time constant to lower tc. Increasing of bushing temperature decreases the dominant time constant too. Reference measurements on bushings are very helpful in interpreting the RVM results. When a dry and new condenser core is measured, the RVM dominant time constant is very high, over 1000 s at 22 °C. Two or more dominant time constants imply an inhomogeneous (i.e. partly wet) bushing condition, as shown in the purple curve of Figure 5.2.3.10.

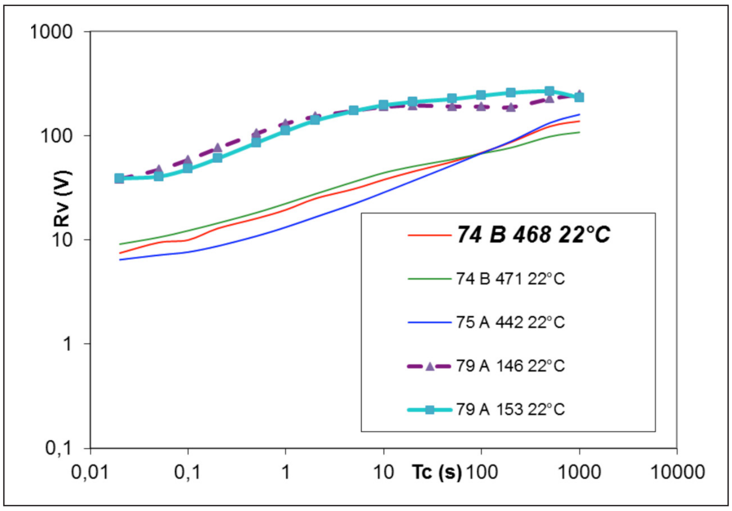


Figure 5.2.3.10: RVM measurement results from different bushings at a same temperature. Upper curves show poor condition while lower curves represent bushing in good condition

Figure 5.2.3.11 shows some RVM results for varying water content in the paper at the same temperature. Increases of the moisture in the insulation distinctively moves dominant time constant to the left. For a moisture change from 0,5 % to 4 %, the dominant time constant decreases more than three orders of magnitude.

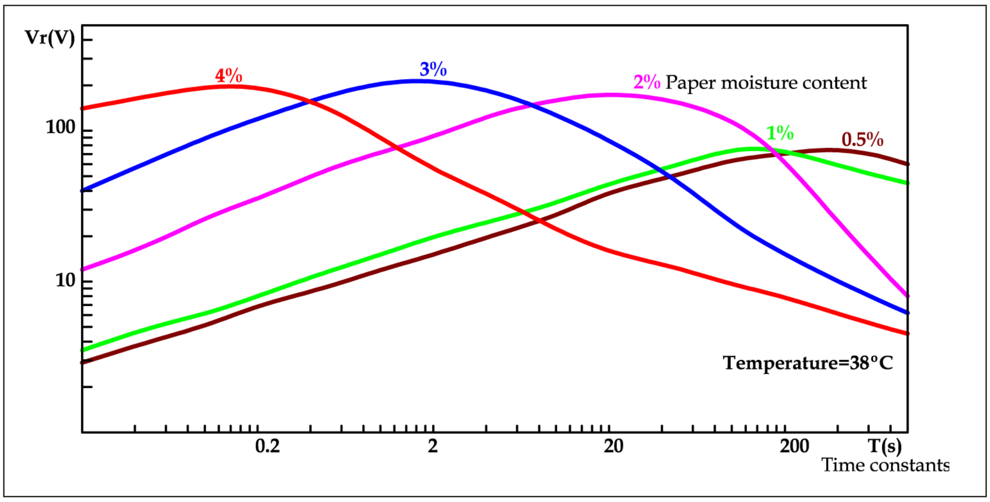


Figure 5.2.3.11: Polarization spectra for various moisture content in the paper determined by RVM method, [5.2.3.9]

Dielectric response methods are still in the research stage and new analysis methods are frequently published. Recent publications present promising FDS or DFR analysis on OIP bushings based on the individual temperature correction (ITC) method [5.2.3.10] and [5.2.3.11].

5.2.4. Winding resistance

Power transformer DC winding resistance measurement is a well-known and widely used diagnostic technique with many modern approaches such as induced voltage compensation [5.2.4.1], and AC impedance with different frequencies [5.2.4.2]. The purpose of a resistance test is to find high-resistance contact between joints in the windings, and in the leadwork connecting the windings, tap changers and bushings. The main disadvantage is error caused by inaccurate winding temperature determination. A winding temperature estimation error of 2,5 °C causes an error in resistance of approximately 1 % (for copper windings). Compounding this is the very high inductances and low resistances, so the measurement method should be adapted to this. The bushing's conductive resistance is only a small fraction of the winding resistance. That is the reason why this method is used only for detail location of poor bushing joints (detected by i.e. IR scanning) and checking of remedial work quality.

In figure 5.2.4.1, overheating traces on the bushing's upper connection are shown, [2.1.4]. Overheating was detected by IR scanning: temperature difference compared to a healthy bushing was 65 K (corrected to rated load). Winding resistance measurements were performed before and after the remedial work (replacement of the poor multi-contact (multi-lam contact), Figure 5.2.4.1, left). The resistance difference between phases was 0,87 % before the repair. The resistance after the repair was almost equal in all of the phases.

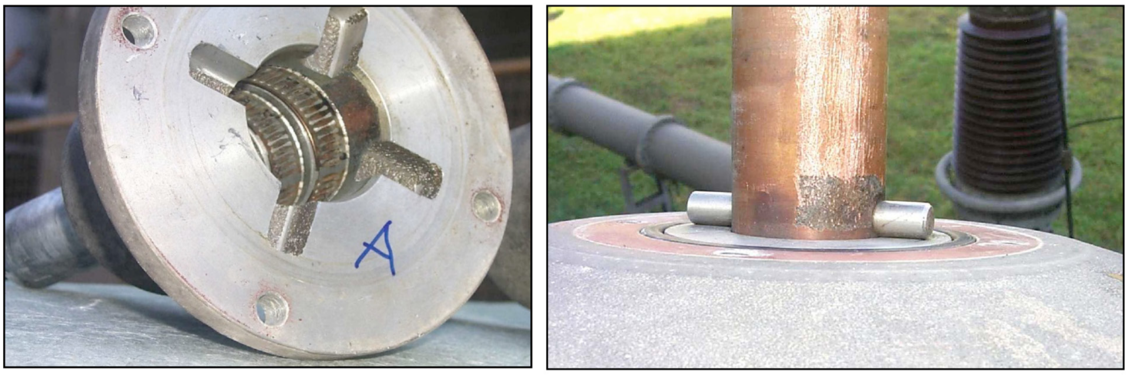


Figure 5.2.4.1: Overheating traces on a 220 kV bushing upper connection (left: on the multi-contacts and upper aluminium connection, right: on copper bolt above bushing head)

As can be seen from the above example, the relevant resistance change may be quite small – even below 1 %. Such measurement repeatability can be obtained on-site only in successive measurements when winding temperature change can be neglected. It should be noted that the DC current heats the winding, and because of that, it shouldn't be too high, but it should be high enough to saturate the magnetic core. Normally, DC current in the range of 1 to 5 % of the rated transformer current is a good choice for precise measurements.

5.2.5. Infrared scanning

Infrared (IR) scanning is one of the most widely used and established diagnostic methods in the world, refer to Table 3.4.4.1. Transformer bushings are periodically monitored by an infrared camera, usually together with other current conducting parts of the substation and overhead lines. The method is used for temperature (overheating) determination of the joints, bushings, turrets and tank, without any direct contact with the scanned object, but it is essentially restricted to outside visible parts. Recognising overheating deep inside generally requires a lot of experience and it is not always possible. The transformer should be energized and, for accurate diagnostics, loaded with at least 50 % of the rated load.

Note: IR measurement on a lightly loaded transformer may lead to an erroneous conclusion because of the very large influence of the load factor. At a 10 % load, a 1 K measured temperature difference corelates to a rated load as temperature difference of 100 K (temperature is proportional to the square of the load current), refer to (5.2.5.1 through 5.2.5.4). A 1 K temperature difference can easily be attained on a transformer bushing because of actual transformer heat flow from many sources and reasons.

The method can be applied in an on-line (continuous) monitoring system and, while it is commercially available, it is rarely used. The accuracy of the measurement is affected by heat radiation (emission) factors, distance, and atmospheric conditions. These factors mostly affect the absolute temperature value and are compensated in temperature difference measurement. This is the reason that the measured temperature difference of similar objects of two phases, made from the same material and exposed to the same load, is very accurate (normally much less than 1 K). To minimise the influence of atmospheric conditions, it is recommended to perform the IR measurements during the night or on a cloudy day, with a wind speed less than 20 km/h. An example of a bushing IR scanning is shown in Figure 5.2.5.1.

Diagnostic decisions are based on two temperatures: temperature difference and (absolute) temperature, both scaled to the rated load:

$$\vartheta = T - T_o \qquad \vartheta_n = \frac{\vartheta}{k^2} \qquad T_n = \vartheta_n + T_{om} \qquad (5.2.5.1,\ 2\ \text{and}\ 3)$$

The calculation of temperature rise or temperature difference of comparable parts (1 and 2) at rated load is:

$$\Delta\vartheta_n = \vartheta_{n1} - \vartheta_{n2} = \frac{\vartheta_1 - \vartheta_2}{k^2} = \frac{T_1 - T_2}{k^2} = \frac{\Delta T}{k^2} \qquad (5.2.5.4)$$

Where:
ϑ – temperature rise
ϑ_n – temperature rise scaled to rated load
k – relative load during measurement (S/S_n)
T – measured temperature
T_o – ambient temperature
T_n – temperature scaled to rated load and T_{om}
T_{om} – maximal average daily temperature (according [2.1], 30 °C)
Δ – symbol for difference

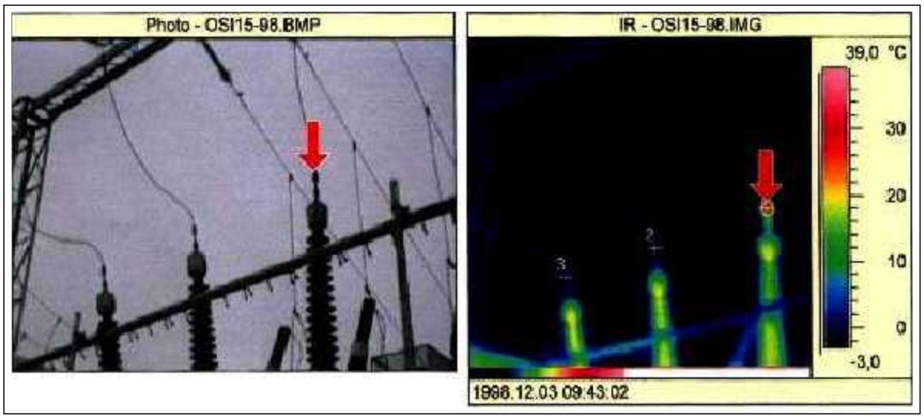


Figure 5.2.5.1: Overheating of a 220 kV bushing joint (upper contact) marked with red arrow (left: visual and right: IR spectrum)

Decision criteria for the available temperature difference (°C) between similar and comparable objects (bushings, etc...) at rated load [2.1.4] is:

$\Delta\vartheta_n < 5$:	Normal condition
$5 \le \Delta\vartheta_n < 10$:	Caution: check and repair during the next scheduled maintenance outage
$10 \le \Delta\vartheta_n < 35$:	Caution: advance the scheduled maintenance outage for repair
$\Delta\vartheta_n \ge 35$:	Extreme condition: remove from service for repair

The severity of the actual case may be reduced if the absolute temperatures are far below the standard limits, but be aware that the temperatures inside of the bushing may be much higher than on its visible surface.

Decision criteria for an (absolute) bushing temperature (parts in contact with insulation) at rated load and T_{om}= 30 °C, [2.1]:

OIP, Solid type (porcelain):	105 °C
RBP, RIP, RIS:	120 °C

The detection of a low oil level on OIP type bushings is possible as can be seen in Figure 5.2.5.2., [5.2.5.1]. The central bushing clearly shows a typical thermal pattern for a lower level of oil: the upper part of the bushing is colder and the lower part is hotter than the comparable left and right bushings.

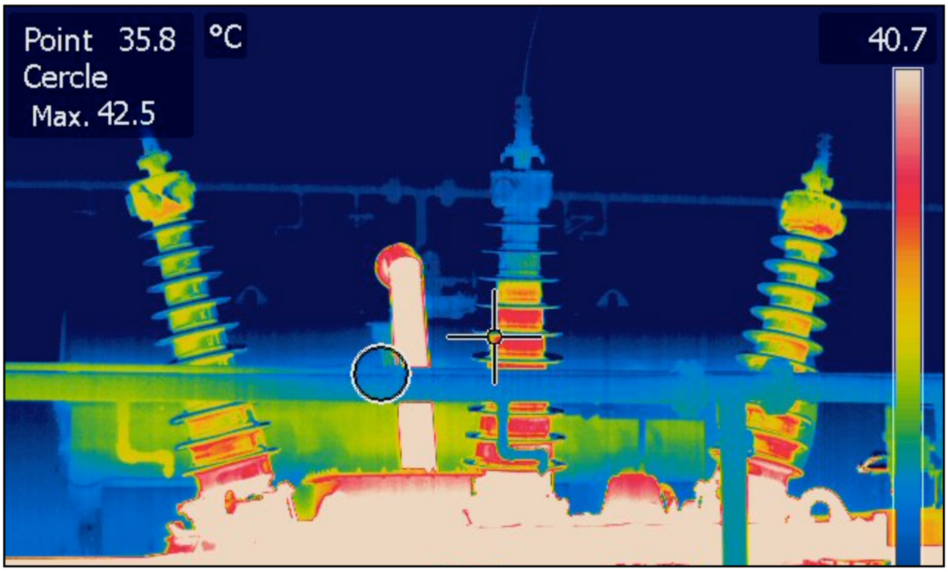


Figure 5.2.5.2.: Low oil level indication on the central bushing by IR

It is suggested that any significant difference in thermal pattern, when compared to comparable or new bushings, should be analysed in a reasonable time frame. For example, and according to experience, a 5 °C temperature difference of a bushing's upper envelope should be considered as significant.

5.2.6. Partial discharge measurements

Partial discharge (PD) represents local dielectric overstress or weakness expressed as a partial breakdown of a complex insulation system without voltage collapse. PD deteriorates insulation systems and as time passes, they can cause a breakdown. PD activity typically occurs within insulation voids (poor impregnation), on ungrounded metal objects in an electric field, or due to the intense electric stress on the insulation surrounding sharp edged/shaped electrode. The last-mentioned PD is related to a high non-uniform electric field. In a uniform electric field, PD onset is often immediately followed by a breakdown. PD can be measured or detected thorough their effects. There are several PD detection methods: electrical (in wide frequency range), mechanical (acoustic signal, oil pressure rise), optical (light - not relevant for bushings) and chemical (DGA - gasses dissolved in oil produced by PD). It should be noted that all mentioned PD detection methods are not relevant for all bushing types.

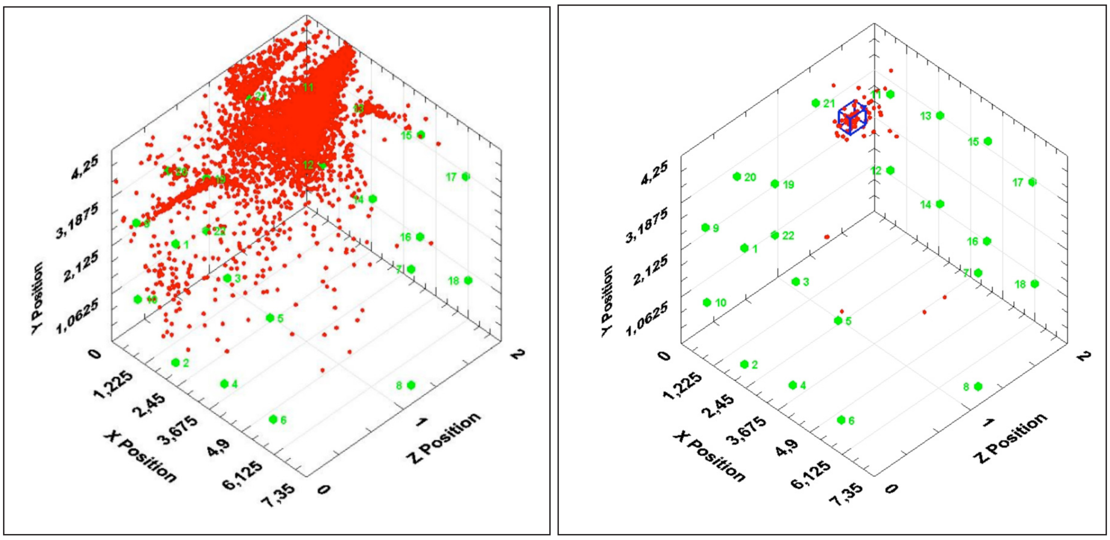
PD on-site measurement on bushings can be performed by using of three methods: conventional electrical method [5.2.6.1], acoustic emission (AE) methods [5.2.6.2] and, for OIP bushings, DGA, refer to section 5.3.2 and oil pressure, refer to section 5.5.4. At the present time there is no relevant information about on-site bushing PD measurement by using of UHF sensors, [5.2.6.4]. Reference [5.2.6.5] give an example of UHF PD measurement on bushing performed in laboratory. It should be noted that this technique does not require test tap for PD measurement. This measurement will be of interests of JWG A2/D1.51: Improvement to partial discharge measurements for factory and site acceptance tests of power transformers. The main problem is the very low amount of PD value allowable for bushings according to relevant standards (5 pC to 10 pC for OIP and RIP bushings), [2.1], that measuring methods should be able to detect. Such a small amount of PDs can be easily masked by many PD sources inside and outside of the transformer such as corona from the switchyard and the many sources of PD inside of a transformer (the allowable PD in the transformer is more than ten times greater than that for OIP and RIP bushings). The conventional electrical method is, especially with respect to the bushings, very sensitive to such disturbance or noise, refer to section 5.5.6, especially on-site.

As a coupling device for bushing PD measurement measuring or voltage tap can be used so as external coupling capacitor. The test method outlined in [5.2.6.1] is a useful tool, because it is a sensitive method and can be calibrated. High frequency current transformers can be also used as a coupling element. Modern multi-channel PD measuring systems can record the PD on all channels simultaneously with modern digital data handling and presentation. These can help to separate the different PD sources from each other, including the intensive electromagnetic noise internal and external to the transformer, [5.2.2.2.3], [5.2.6.3].

According to [5.2.6.1], the upper limit for the PD measurement frequency is 1 MHz for wide band systems. This doesn't allow the differentiation if the PD is coming from the transformer or if it is inside the bushing. Because of this, in some cases, it might be useful to work with higher measurement frequencies. If the PD spectrum has a very high amplitude at high frequencies this indicates the PD source close to the coupling point and is probably inside of the bushing. If the PD is highly damped at high frequencies, the PD source is probably far from the bushing and inside the transformer. If the case is inconclusive, it might be necessary to remove the bushing for PD measurements in a HV laboratory.

5.2.6.1. Acoustic emission method of partial discharge measurements

Acoustic emission (AE) or the ultrasonic method of detecting PD is based on the fact that the electrical energy of the PD transforms into a mechanical energy, an ultrasonic acoustic wave that spreads through the transformer to the tank wall. These waves are detected with piezo-electric sensors, mounted on the tank, which transforms this mechanical wave into an electrical signal. The AE PD measurement method is very resistant to electrical disturbances, but their main purpose isn't PD measurement but rather PD location in space (i.e. inside of the transformer tank or even inside of the bushing), [5.2.6.1.1]. This method determines the PD location by triangulation, which can be around the leads and connections, around the bushing end insulation and, with less sensitivity, inside of the bushing. Standard measuring equipment consists of from several to more than 20 resonant sensors, and a computer acquisition and signal analysis system. Sensors are piezo-electric type, with a resonant frequency of 150 kHz, and shielded to eliminate electromagnetic disturbances. The band pass is between 70 and 200 kHz, which makes them sensitive to PD, and less sensitive to external noises. The position of each sensor is mapped in a coordinate system along with the transformer tank dimensions (actually it represents a 3D coordinate system). Placement of the sensors mostly depends on the construction of the transformer while considering the most critical points of possible PD sources. If the bushing is suspected acoustic sensors should be positioned near the bushing flange and in the vicinity of the bushing oil end (turret or similar). More reliable results are obtained by re-positioning the sensors over two or more tests to refine the location of the AE activity. Some of the sensors detecting the lowest levels of emission should be moved to the area of greater acoustic activity.



Note: Red dots represents the AE PD findings, green dots represent the sensor position on the transformer tank

Figure 5.2.6.1.1: AE measurements result before filtering (left) and after filtering (right)

After measurement, the results should be filtered by energy, frequency, and other parameters with the aim of obtaining a distinguished cluster of "findings" in the space, Figure 5.2.6.1.1. This cluster represents the most probable location of AE source i.e. PD. In good condition, even a less than 100 pC PD source can be located within approximately ± 0,2 m.

The location of the AE PD findings (triangulated sources) can be outside of the transformer tank, as can be seen in Figure 5.2.6.1.2, [5.2.6.1.2]. The PD findings are along transformer MV bushing. The actual PD source was found on the top of the bushing.

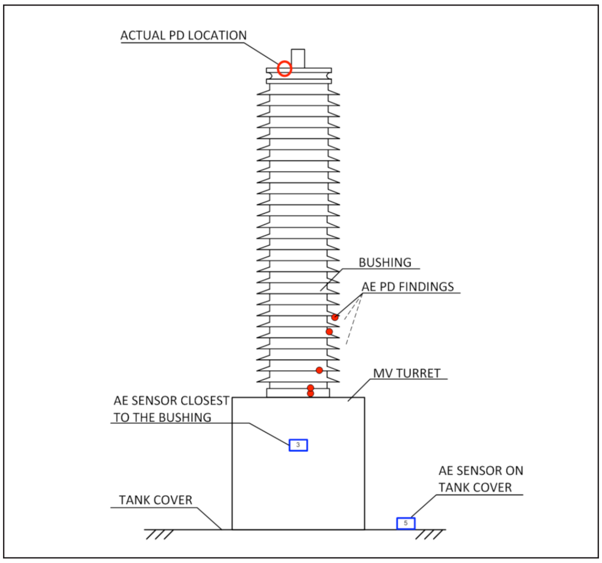


Figure 5.2.6.1.2: AE PD findings and actual location on bushing, [5.2.6.1.2]

Since the method detects ultrasonic acoustic waves spreading through the tank, it can locate other deficiencies that generate an ultrasonic signal such as local overheating in oil (poor contacts, joints, bushing connections) and which gives this method an additional and very useful ability.

5.3. Measurements on bushing oil sample

This measurement is significant for OIP bushings only, [5.3.1]. Some other bushing types (RBP or RIP) may have oil in the space between the upper envelope and the bushing condenser body. In these cases, oil is the secondary insulating medium and the test results are less significant. One of the main problems is in bushing oil sampling. Bushings is a sealed breathing system containing the very small amount of oil compared to other HV equipment. Oil sampling can easily cause a significant and undesirable pressure change that can lead to bushing failure, refer to section 4.1.2. This is the reason that oil sampling is rarely performed in regular intervals. It is mostly performed after some other bushing diagnostic methods indicates a problem or inconclusive result.

It should be noted that bushing oil does not communicate (come in contact) with transformer oil, so transformer oil analysis is not relevant for the bushing oil. However, some bushing failure modes can affect the transformer oil DGA results if the electrical or thermal overstress happened in the transformer oil, refer to section 4.1.2. (Current path and contact problems) and 4.1.3. (Bushing end shield problems). Of course, if the OIP bushing lower envelope ruptures, the oils mix and gasses from bushing oil will dissolve into the transformer oil.

5.3.1. Oil sampling from OIP bushings

Before taking an oil sample from an OIP bushing, the general rule is to always consult the bushing manufacturer and the testing biolaboratory about the following:

- The oil sample quantity which can be extracted from bushing without toping-up. It is suggested that this information should be listed in the OIP bushing technical data.
- Which amount of oil is required for the desired analysis?
- Should the bushing be topped-up with oil after sampling, and if so, with what type of oil?
- Are special fittings or tools required?

Appropriate information can be found in the bushing manufacturer’s literature, [5.3.1.1], [5.3.1.2], [5.3.1.3].

Oil sampling should be completed by experienced staff, refer to ASEAN data (improper oil sampling often leads to a bushing failure), [3.2.8], and in according to [5.3.1.4], [5.3.1.5]. An appropriate sampling kit and vessels (syringes, bottles) is required, Figure 5.3.1.1. Oil samples should be protected from light and shocks. For glass vessels wrapping them in aluminium foil provides good protection from light. Each sample should be properly labelled according to [5.3.1.4]. Oil sampling from OIP bushings without an oil level gauge is not recommended.

Figure 5.3.1.1: Oil sampling kit, an example

5.3.2. Dissolved gas analysis

Dissolved gas analysis (DGA) is one of the most powerful diagnostic tools for condition assessment of oil-immersed paper-insulated equipment. The method is based on the fact that electrical (PD and arcing) and thermal overstressing will generate a certain amount of gasses (mainly H_2, C_xH_y, CO and CO_2). These gasses are soluble in oil and thus they can be measured from an oil sample. The measurement method is based on gas chromatography, [5.3.1.5]. The decision criteria for mineral oil is well developed, [5.3.1.6]. Bushings often use insulating liquids other than mineral oil, so consult with the bushing manufacturer before DGA interpretation.

As usual for transformers, DGA interpretation is based on gas ratios. Four fault types are recognized for OIP condenser type bushings:

- PD (due to poor impregnation, cavities caused by humidity, saturation with gasses, loosely wounded paper, refer to section 4.1.2. (part “Gas bubble evolution”), and 4.1.3. (part “Core cracking and delamination”).
- Low energy discharge due to test tap sparking, refer to section 4.1.1. (part “Bushing rigid connection to the switchyard”), tracking, refer to section 4.1.3. (part “Electrode end problems”).
- High energy discharge
- Thermal fault, refer to section 4.1.2 (part “Current path and contact problems”).

In simple terms, hydrogen is the dominant gas for PD. For discharges, whether of high or of low energy, acetylene is produced in addition to hydrogen. For thermal faults, ethylene is produced and also the ratio of carbon dioxide to carbon monoxide changes and falls outside normal limits. According to [5.3.1.6], the 95 % typical concentration of gasses dissolved in the bushing’s oil are shown in Table 5.3.2.1. New DGA limits and OIP case studies are in the consideration of WG D1/A2.47: New frontiers of Dissolved Gas Analysis (DGA) interpretation for power transformers and their accessories.

Table 5.3.2.1: 95 % typical DGA concentrations in OIP bushings in ppm (ml/l), [5.3.1.6]

Gas	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Concentration ppm (μl/l)	140	40	2	30	70	1000	3400

5.3.3. Moisture in oil

Traditionally, OIP bushing moisturising is one of the more common failure modes. Moisture can enter the bushing through a poor bushing sealing system or through cracks in the constructional elements or it can be chemically released in certain circumstances, refer to section 4.1.4. The measurement of moisture content in the oil can confirm what another diagnostic method has indicated. Measurement is performed by coulometric Karl-Fischer titration, [5.3.3.1].

Based on the Polish research performed on oil samples from about 170 OIP bushings in service, age in the range of 12 to 42 years old, revealed that the 90 % typical value of moisture content is below 10 ppm (mg/kg), [5.2.3.7].

5.4. Condition diagnostics of condenser type bushings without a test tap

A test tap is essential for on-site electrical measurements (capacitance, tanδ, and others) on a capacitance-graded bushing, mounted on a transformer. Without it, the bushing parameter will be masked by the much more prominent transformer insulation parameter. Old bushings without a test tap are still in service today. The problem of how to measure dielectric parameters on such bushings can be solved by isolating the bushing flange from the tank and it will then act as an artificial test tap, [5.4.1]. The bushing flange can be insulated from the tank by using insulating gasket and washers for insulation of the screws, Figure 5.4.1.

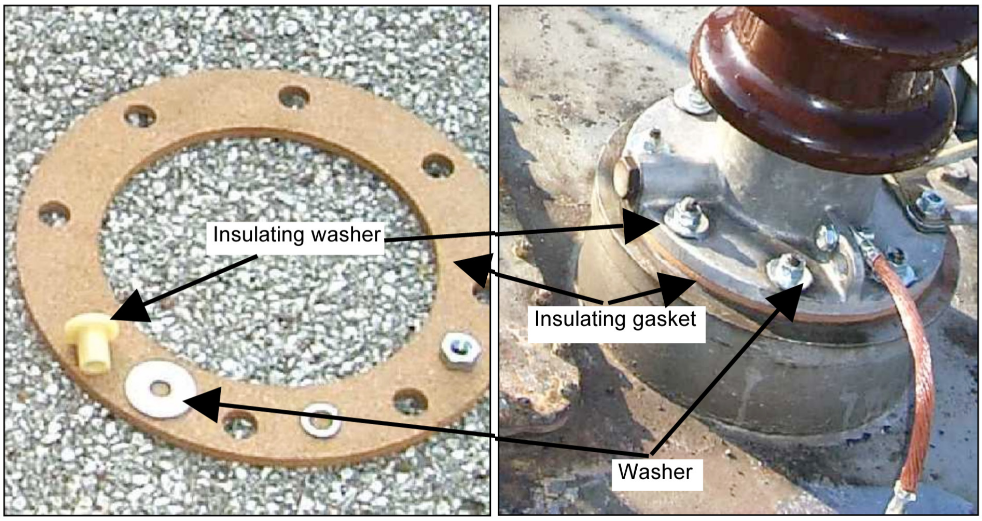


Figure 5.4.1: Bushing flange insulated from the tank (right) and used insulating material (left)

The insulation resistance between the flange and the tank shouldn't be very high for accurate measurement, it depends on the measurement method and the instrument used. For a transformer-type measuring bridge, 10 kΩ is enough. The insulating resistance can easily be checked on-site (before checking transformer should be properly vented). Of course, the copper grounding strap should be removed during measurement.

5.5. Bushing on-line (continuous) diagnostic methods

According to experience, an incipient bushing failure (faulty condition) can quickly (1 ms) or slowly (10 years) develop into a failure with a forced outage. Quickly developing failures are usually associated with insulation breakdown caused by overvoltage. No diagnostic method exists, on-line or off-line, which can prevent such fast-developing incipient failures. In fact, a very fast developing incipient failure is practically the same as a terminal failure because there is not enough time for remedial action. On another hand, moisture ingress, or low intensity overheating may occur over a long time before a bushing terminal failure occurs with a forced outage. The main diagnostic advantage of continuous (on-line) monitoring compared to periodic (off-line) monitoring is the much shorter detection time interval, refer to Figure 5.5.1. Off-line diagnostics will usually not detect an incipient failure that will develop into a failure with a forced outage in less than approximately half a year, mainly because of the regular testing interval that is not normally shorter than one year for bushings, refer to Figure 3.4.4.4. The fault detecting time interval for on-line bushings diagnostic methods varies from approximately a minute to a day, depending on the bushing monitoring system decision-making settings for alarm or trip.

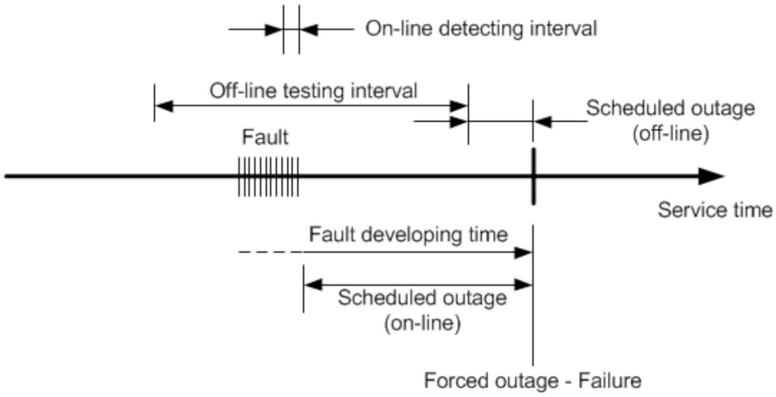


Figure 5.5.1. Bushing off-line and on-line initial failure (fault) time recognition and related scheduled outage

Compared to the off-line (periodic) methods, the on-line (continuous) measurement has several important advantages:

- Recognition of faults (incipient failure) in the very early stage because of continuous measurement. This helps to maintain transformer in service until incipient failure has developed to critical stage.
- Measurements at operational temperature – diagnostic methods are more sensitive and reliable at elevated temperatures.
- Measurement at rated voltage – represents a more realistic bushing condition.

Another important benefit of an on-line monitoring system is the data storage and analysis capabilities, including the recent so-called intelligent monitoring system that must feature advanced bushing condition analysis. Such bushing monitoring systems are improving every year by year with technological evolution, [5.5.1], [5.5.2], [5.5.3]. Although continuous monitoring systems are not directly related to transformer fleet health indices, the health index system often incorporates on-line monitoring systems data. This may significantly improve the transformer's availability and real-time reliability [5.5.4], [5.5.5], [5.5.6].

It should be recognised that all on-line (continuous) electrical measurement (capacitance, tanδ, PD and overvoltage measurements) starts at the bushing test tap, Figure 5.5.2.1. The bushing test tap is a part of the on-line measuring system [5.5.7], [5.5.8]. It is well known that the test tap can cause bushing failure (refer to section 4.1.3, part "Test tap problems") especially if the tap remains open, Figure 5.5.2. Today, with the usage of on-line monitoring systems, the test tap is used continuously, which is a new challenge. The current situation (especially in some markets) is the existence of numerous physically-different measuring tap designs requiring numerous test tap adaptors adjusted to each test tap. From this aspect, a unification of the test tap design is recommended [5.5.7], [5.5.9], [5.5.10]. This will increase service reliability of the bushings, and therefore the reliability of the on-line monitoring system. It is also recommended that the continuous operating voltage capability and design value of the lighting impulse withstand voltage of the test tap should be listed in the bushing's technical data.

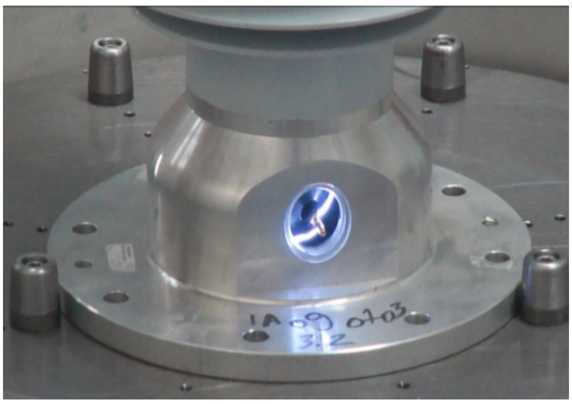


Figure 5.5.2. Energized bushing with an open test tap - can be destroyed in a relatively short time

5.5.1. Bushing capacitance on-line monitoring

Bushing capacitance on-line monitoring is much easier and simpler to perform compared to bushing tanδ monitoring because only phasor magnitude should be measured, Figure 5.2.2.1. Voltage measured by using the bushing as a voltage divider is compared with the relevant phase voltage measured in the system. Any disturbance between these voltages implies a bushing HV capacitance (C_1) change. Alternatively, comparison of the divider voltage of one phase with average voltage of other two phases can be used (this will partly eliminate the voltage asymmetry in a three-phase system with earthed neutral). Summarizing simply, if the voltage of one phase suddenly changes from its expected value, then the bushing capacitance is suspected, Figure 5.5.1.1, [5.5.1.1]

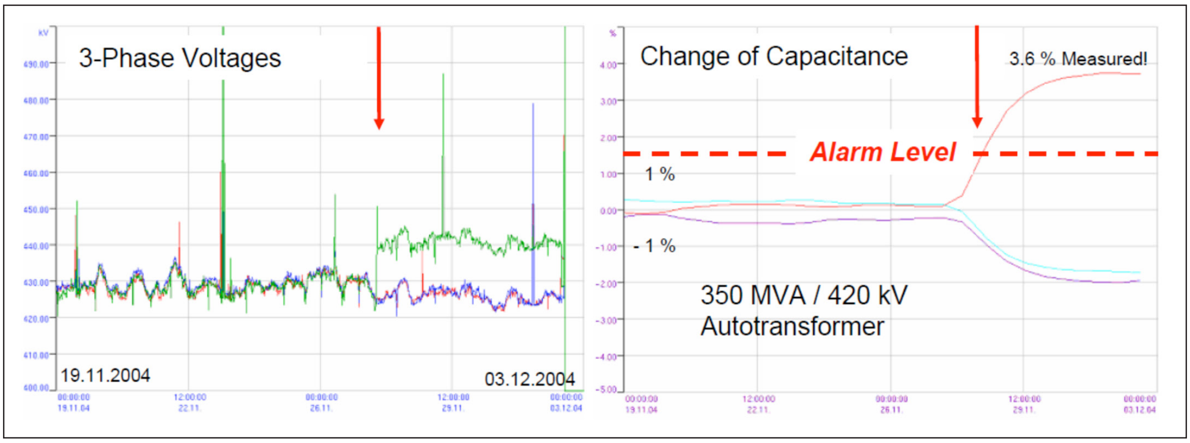


Figure 5.5.1.1: Capacitance change calculated from voltage measurement by using the bushing as a divider (left: voltage recorded; right: calculated capacitance change)

In section 5.2.2.1, for off-line (periodic) measurement of OIP and RIP bushings, it is recommended that if the bushing's capacitance increase to a value that corresponds to short-circuited adjacent electrodes, it should be replaced. For on-line (continuous) measurement, it can be recommended that the bushing should be replaced if capacitance change for off-line measurement is doubled. This is suggested because the presence of continuous measurement is expected to prevent capacitance increases that may jeopardize the bushing's electrical integrity. This means that if the on-line (continuous) bushing capacitance monitoring system registers capacitance change large enough for a recommended off-line measurement bushing removal, then this should be considered as a first stage alarm (caution). In this case, an off-line capacitance measurement should be taken for control purposes. If the result confirms capacitance change plans for the bushing's replacement should be prepared. Also, the bushing monitoring system should be continuously active.

Bushing capacitance on-line monitoring seems to be a very reliable method in HV and UHV networks with relatively small voltage asymmetry and harmonic content. Weather conditions (rain, snow) have a small influence on the results and normally can be neglected. In addition to bushing short-circuited condenser detection (capacitance increase) capacitance change may also indicate test tap problems (capacitance decrease), and thus prevents bushing terminal failures.

5.5.2. Bushing tanδ or PF on-line monitoring

The basic difference compared to capacitance monitoring is that both part of the complex phasor magnitude and the phase angle should be monitored. As mentioned in section 5.2.2., phase angle measurement must be very accurate. For example, if we measure a tanδ of 0,35 $\cdot 10^{-2}$ and the angle error is only 0,1°, the error in tanδ will be about 50 %. That means this measurement is exposed to various influences including weather conditions (rain, snow, fog, very high humidity, low temperature), dirt on the bushing's surface and the electromagnetic influences in the field. For off-line tanδ measurement, it is simply assumed that the bushing surface should be cleaned and testing during inclement weather conditions should be avoided. The interpretation of the bushing tanδ monitoring results should consider these influences. Of course, if the bushing tanδ is monitored, all data for the bushing capacitance monitoring are available, Figure 5.2.2.1.

For bushing tanδ (and capacitance) monitoring three basic methods can be used [5.5.2.1], [5.5.2.2]. Each method has its advantages and disadvantages.

- **Sum of phasors**, Figure 5.5.2.2. The advantages of this method are: it is simple and has good sensitivity, while requiring less cabling. The disadvantages are that this method is prone to asymmetric fluctuation of the system compared to the initial (learning) period and this method cannot be used on alone single phase transformer.
- **Bushing-to-bushing comparison.** The advantages of this method are no network unbalance problems, and capability to monitor the bushings on two (or more) transformers. The disadvantages are that this method is available only if two (or more) transformers are operating continuously on the same busbars, and more cabling is required.
- **Voltage transformer reference.** The advantages of this method are that is an “absolute” measurement (voltage transformer provides magnitude and phase angle), and no network unbalance problems. The disadvantages are more cabling (voltage transformers are usually placed far away from transformer) and very often they are not available for this purpose.

The choice of method must be based on the measurement requirements and equipment availability in the substation. It should be noted that staff are often reluctant to add more cabling in existing switchyards and usage of voltage transformers in a monitoring system.

The basic measuring scheme of the bushing monitoring system is schematically shown in Figure 5.5.2.1. The signal is coupled from the test tap of the bushing by a tap adapter and a measuring impedance, [5.5.7]. The current path provides safe connection to the earth, thus preventing the appearance of dangerous voltage at the test tap. Several levels of voltage limiting devices are built-in to the test tap adapter, measuring impedance and cubicle. Furthermore, the signal is connected to a DSP (digital signal processor) which measures amplitude and phase angle related to the signals from other bushings or the secondary terminal of a voltage transformer.

In the sum-of-phasors method, Figure 5.5.2.2, the resultant phasor is calculated from the signals of three bushings. Under normal conditions in a symmetrical three-phase system the sum of the bushings (leakage) current I_{Ro} is very small. Even a small change in any current phasor will result in relatively large change in the resultant phasor. Changes in capacitance and tanδ, along with which bushing is suspected are then calculated from the change of the resultant phasor. This technique provides good sensitivity to changes of tanδ. Voltage asymmetry in a three-phase system may reduce this sensitivity significantly.

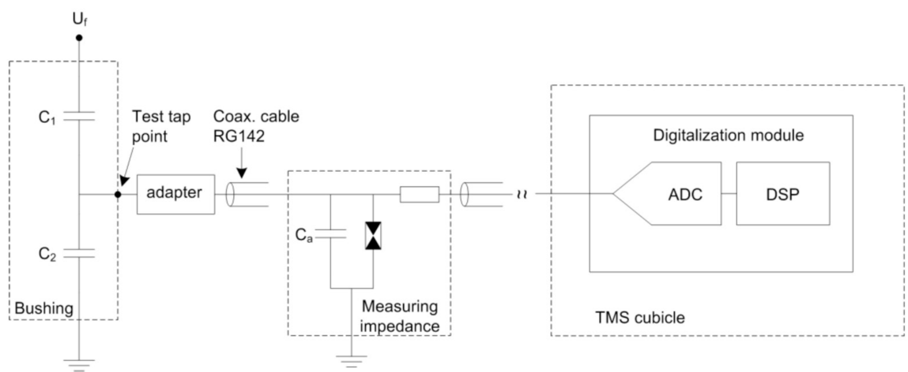


Figure 5.5.2.1: Schematic drawing of bushing monitoring system basic measuring path

If all three bushing shows similar changes in leakage current, they are probably caused by weather condition.

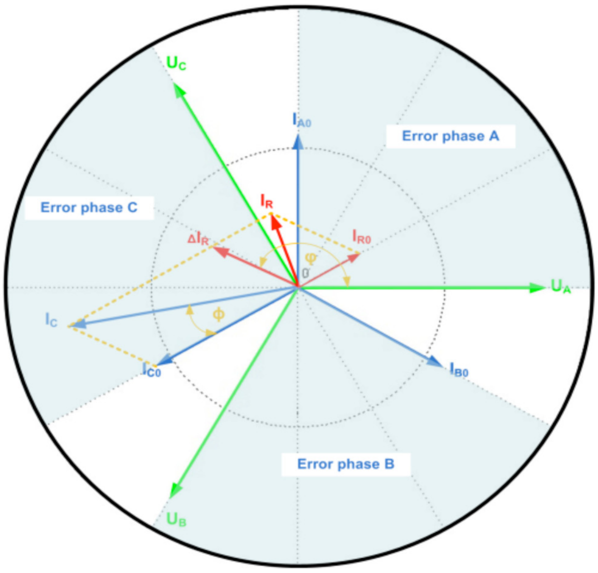


Figure 5.5.2.2: Sum of phasor bushing monitoring method basics (current phasors are not to scale)

The bushing-to-bushing comparison method is used for monitoring of the bushings on two (or more) transformers that are operating on same bus bar. While each set of bushing can be monitored independently using the sum-of-phasors method, bushing-to-bushing method provides more information by comparing signals from pairs of bushings that are operating on same line-to-earth voltage. Changes in bushing capacitance and tanδ are calculated from changes in the phase angle and the ratio of leakage current amplitudes. When disturbances are recorded, off-line capacitance and tanδ measurement is suggested, and should be performed on all transformer bushings.

If the signal from the secondary side of the voltage transformers is available, the absolute value of capacitance and tanδ can be measured as is theoretically defined. This method provides the best results, but often it is not possible to use it because either there are no available voltage transformers in the substation, they are far from the transformer or connection of voltage transformers to the monitoring system is not allowed by staff.

5.5.3. Bushing creepage current on-line monitoring

Bushing creepage current is current along the surface of the upper envelope. It should be distinguished from bushing leakage current which is current through the bushing's HV capacitance (C_1) – term often used in some countries. Creepage current is strongly affected by the upper envelope material and its hydrophobicity, (refer to section 5.2.1), as well as pollution and weather conditions.

Creepage current is measured by the use of a small ring electrode placed just above the flange in the non-graded area of the bushing, [5.5.3.1]. This current, for a new and clean upper envelope can reach about 10 μA in dry condition and does not increase much in wet conditions. For an old and polluted upper envelope, it can reach about 30 μA in dry conditions and up to more than 1 mA in wet conditions. The method can be used in highly polluted areas as an indicator of the bushing upper envelope's surface quality. Generally, this method is used rarely.

5.5.4. Bushing internal pressure on-line monitoring

As mentioned in section 2.1, OIP bushings are equipped with a closed breathing system. That means that gas and oil in the bushing cannot mix with the surrounding air or oil until the bushing sealing system is perfect. A pressure change is caused by a change in temperature, but bushing's pressure does not depend simply on temperature only. The phenomenon is more complicated because of the gas' solubility in oil increases with pressure and is also influenced by temperature and type of gas. To simplify - each OIP bushing type has a specific pressure dependence with temperature and time.

PD in oil impregnated paper insulation results in the production of certain gasses, refer to section 5.3.2. This phenomenon tends to increase the bushing's internal pressure.

Bushing internal pressure can be measured by pressure sensors mounted on the bushing flange [5.5.4.1]. In this essence, decision making is simple:

- When the bushing's internal pressure does not follow the normal bushing-specific pressure dependence with temperature, then the bushing sealing system is considered suspect. Bushing visual inspection is recommended with attention to oil leaks and the oil level. If the oil level has decreased – replace the bushing. Please note that the bushing oil may leak into the transformer oil (and vice-versa) and in that case the oil level in bushing can fall or rise. If the sealing system is weak at the top of the bushing (in gas zone of the bushing head), no oil leak will be found. The bushing should be replaced because during rain the bushing may easily suck-in water resulting in a disastrous failure.
- When the bushing's internal pressure rises above the normal bushing-specific pressure dependence with temperature, then PD is suspected. Bushing replacement is recommended. It should be noted that PD will not causes the bushing pressure to increase when the sealing system fails (in this case bushing breathing system is not closed), but poor sealing will be recorded by the internal pressure monitoring.

In both cases a comprehensive study of all monitored data should be performed. Off-line measurement of capacitance and tanδ is suggested to confirm a final decision.

This method is also applied on oil-filled instrument transformers, and experiences can be used for OIP bushings.

5.5.5. Transient overvoltage on-line monitoring

Transformers in service can be subjected to overvoltages with a broad spectrum of frequency, steepness, duration and event recurrence. Bushings are the first transformer component exposed to this. It is well known that they can cause bushing (and transformer) failures, [4.1.3.8], [5.5.5.1]. If failure analysis is performed, it is very helpful to have reliable information on overvoltage existence and its properties. The presence or absence of significant overvoltages can point the failure research in the right direction, [4.1.3.5].

As previously mentioned, the bushing's HV capacitance can be used as part of a high voltage capacitance voltage divider. It should be noted that capacitance graded bushings, due to their coaxial design have very good high-frequency properties, Figure 5.5.5.1. Frequency response measurements reveal no significant disturbances in voltage ratio up to 20 MHz. The obtained response is not as good as a laboratory HV divider, but it is adequate for measuring the high frequency transients for research purposes, and not only service voltages as mentioned in sections 5.5.1 and 5.5.2.

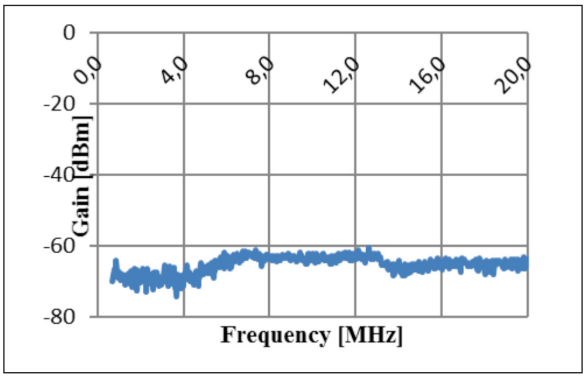


Figure 5.5.5.1: Frequency behaviour of a 123 kV RIP wall bushing as a divider

A transient overvoltage monitoring device consists of a very fast comparator which detects that voltage is out of positive or negative bounds and activates a detector circuit which samples a value of overvoltage. A special mechanism of data storage assures that the complete overvoltage shape is stored. Of course, all systems should have an appropriate sampling rate that fulfils the required frequency range. Modern transient overvoltage monitoring systems allow the recording of even faster overvoltage than the standard lighting impulse voltage shape (1,2/50 μs) for research purposes. It covers most of the overvoltage wave shapes caused by switching operations and atmospheric discharges in the power system. The monitoring system can detect the peak and quantity of overvoltages, and stores each event with a time and date, [5.5.5.2]. Each chosen overvoltage can be analysed, magnified and so on. This information is very valuable in failure analysis. The voltage on a 400 kV transformer recorded by a transient monitoring system in the case of an HV bushing terminal failure (breakdown) is shown in Figure 5.5.5.2. The results revealed that no significant overvoltage appears prior to the bushing failure, [4.1.3.5].

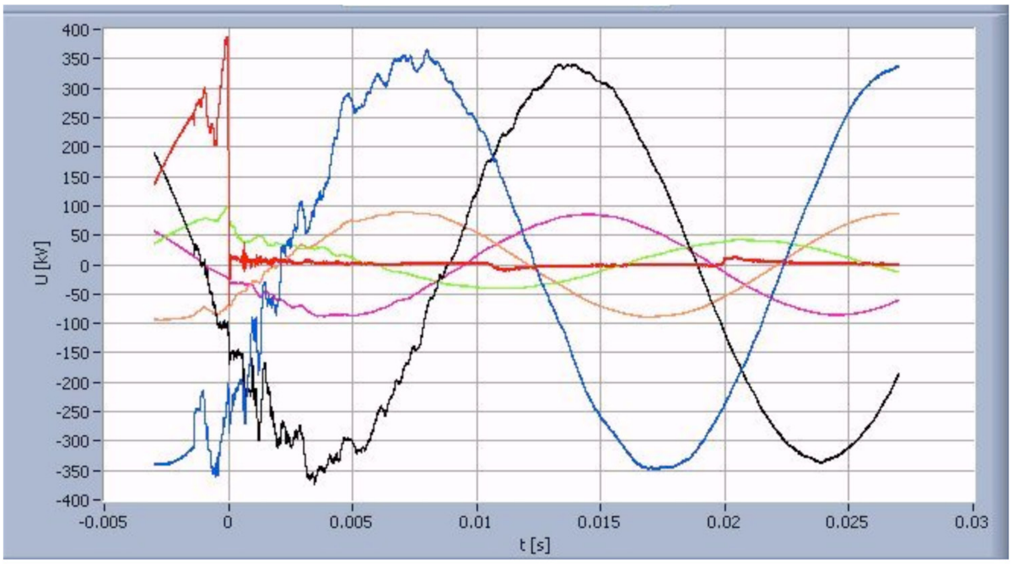


Figure 5.5.5.2: Voltage on a 400 kV transformer in the case of a bushing terminal failure (red line – voltage on failed bushing, blue and black lines – voltages on other two HV bushings, other lines – voltages on MV side)

5.5.6. Bushing partial discharge on-line monitoring

Bushing continuous PD monitoring is performed in the same way as periodic PD measurement by the electrical or AE method. The main differences is the higher level of automation and data storage to enable analysis and research possibilities. The additional problem here is that weather conditions (especially rain, fog and wind-carrying sand) should be considered. Special sensors for the detection of these weather conditions is often used. Data recorded during inclement weather is segregated from other "healthy" data. Measurement frequencies may need to be adjusted, refer to section 5.2.6.

5.5.7. Service experience related to on-line bushing monitoring

Bushing continuous monitoring methods are the most widely accepted among all of the monitoring methods applied to power transformers. According to Table 3.4.4.2, the most commonly used continuous (on-line) diagnostic methods are bushing capacitance monitoring, at 93 %, followed by tanδ or PF, at 64 %, and voltage transients at 21 %. Bushing monitoring service experience is commonly discussed in the literature, [5.5.1.1], [5.5.5.2], [4.1.3.5], [5.5.7.1], [5.5.7.2], [5.5.7.3], and several WG A2.43 members presentations and service experience were dedicated to this topic. It is not so easy to summarize the experiences around the world, but it can be concluded that bushing monitoring is definitely accepted in transformer society for effective prevention of busing failures. According to cases reported, it seems that capacitance monitoring is slightly more effective than tanδ (or PF) monitoring. The reasons for this are maybe because capacitance monitoring as a method is older and slightly more abundant than tanδ (or PF) monitoring, and capacitance measurement is more resilient to parasitic influences and disturbances.

Missing from the experience component in literature is events where on-line monitoring does not prevent the failure of bushing, [4.1.3.5]. Fortunately, these unsuccessful events happened rarely. But despite that, it can be suggested that "unsuccessful" cases should be elaborated in the same way as successful cases. This is definitely necessary to improve bushing monitoring systems. It has also been reported that a monitored bushing failed without warnings because the monitoring system was not in operation. It can also be suggested that the reliability, durability and life expectancy of monitoring systems should be considered.

6. Bushing storage

Storage recommendations for bushings varies depending on the type of construction (RBP, OIP, RIP, RIS, type of sheds, etc.) and the environment for storage. In general, bushings require protection from moisture ingress, ultraviolet (UV) radiation, ozone, corrosion, damage from wildlife and seismic or vibration impact. In these short guidelines, the general protection of bushings is explained together with specific recommendations.

Bushings should be handled by experienced and trained staff/workers. General recommendations about bushing handling can be found in [3.2.8]. Safety measures according to actual rules should always be taken into account as per the manufacturer's handling recommendations. Bushings relevant to this brochure are capacitors and they can store a certain amount of electric energy that can cause an electrical shock and a reflex reaction (i.e. can cause a worker to fall from a ladder). To prevent this, it is suggested to handle bushings with the HV condenser short-circuited.

To begin with, short-term and long-term storage should be distinguished. These terms depend on the severity of storage conditions. Normally, storage longer than one year or so should be considered as long-term storage.

For short-term bushing storage, the best method is to use the original packing crate in a dry area, protected from wildlife and direct sunlight. It is recommended to wrap the bushing's oil part with plastic foil and insert a desiccant bag if possible, to prevent moisture ingress (especially important for RBP and RIP).

For long-term bushing storage, the best method is to store bushings in the vertical position, Figure 6.2. In the case of RBP and RIP, the oil part should be immersed in oil. It is important that an appropriate stand is designed according to the relevant seismic regulations. All connection points of the bushings should be protected from corrosion by applying a protective lubricant or another easily removable protective substance. These connection points include the locations of the current-carrying terminals at both ends of the bushing as well as the gasket surface of the mounting flange. An appropriate upper bushing part protective cover is also recommended regardless of storage location.

The primary concerns about the storage of the various type bushing types are:

RBP bushings: The main concern is the moisture absorption at the oil end of the bushing. The RBP bushing condenser body often has cracks, especially once it has been in service, Figure 4.1.3.1. The cracks can usually be tolerated, to some extent, if they are oil filled, but when the inboard end is not immersed in oil, the oil can drain out, and the moisture can easily enter these cracks. If cracks are observed, vacuum filling should be used when installing the bushing – especially when a bushing is re-installed (vacuum should be applied with caution as the bushing can be further damaged, contact the bushing manufacturer if possible).

OIP bushings are the most common bushings manufactured in the past and they are still very often as a new bushing. If the inboard and outboard ends are both constructed with ceramic insulators, the only storage concerns are corrosion, moisture ingress, and loss of oil impregnation. During the manufacturing process, the paper is carefully dried and impregnated with oil. However, if the bushing is stored such that the paper is not completely covered with oil, the oil in the paper will drain out. Once this occurs, it is very difficult to force the oil back into the paper, and thus microscopic voids form in the insulation which affects the dielectric performance of the bushing (PD). Therefore, it is very important to store the bushing in the orientation it will be in during service. Therefore, it is strongly recommended that vertically mountable bushings should be stored in a vertical orientation, and horizontally mountable bushings should be stored in a horizontal orientation. If bushings are stored in some other orientation, such as lying down for a vertical bushing, the manufacturer's instructions should be followed. Most vertical bushings will have the paper safely covered with oil if oriented at an angle of inclination of at least 10 degrees with the top of the bushing elevated. Moisture ingress is always a concern with OIP bushings in storage. One contributing factor is the relatively low temperature of the bushing. At lower temperatures, the oil and gas in the bushing contract and the resulting pressure is often lower than atmospheric pressure. Thus, any compromised seals may allow moisture ingress. It is recommended that the bushing is always properly supported in such way that the busing shouldn´t be exposed to unintended stresses to joints with gaskets. With some very large bushings, added external supports are required before lying them down to keep the parts from shifting. Oil sampling can also result in a compromised seal at the sampling location; therefore, one needs to ensure that the gasket is in good condition when reinstalling the plug.

RIP bushings have an inboard end that is machined (processed by turning) such that the paper fibres are at the surface or very close to it and can, therefore, absorb moisture. The moisture then travels longitudinally along the paper layers and becomes nearly impossible to be extracted if the moisture penetrates deep into the bushing condenser body. Even if stored indoors, with unprotected the oil part, the moisture absorption can cause tanδ (or PF) to increase after a few months. Moisture penetration into the RIP body can be visually detected: the oil part (inboard end) of the bushing becomes lighter in colour and the paper structure more or less becomes clearly visible, Figure 6.1 (more examples can be found in [3.2.8]). Dry RIP bushing appear darker with practically no visible paper structure. This phenomenon is not a concern when the bushing is installed, but protection is necessary for long-term storage. Sealed aluminized plastic bags with desiccant will provide adequate protection, provided that the integrity of the bag is intact. Another more robust solution is to store the bushing with the inboard end inside a metal container filled with dry mineral oil, Figures 6.2. and 6.3. The original packaging is generally suitable for storage for up to one year if never opened or damaged. The presence of excessive moisture in the bushings can, in almost all cases, be detected by an elevated tanδ or PF measurement. Most RIP bushings must be stored such that the inboard end is not exposed to UV radiation as such exposure will also damage the bushing.

Figure 6.1: RIP bushing's oil part visual appearance; left: humidified body, centre: humidified body – enlarged, right: dry

RIP bushings can be dried to eliminate surface moisture collected during storage. The bushing should be placed in an oven at a temperature of 70 to 80 °C for 3 to 4 days and, if possible, with a vacuum for a better outcome (consult with the bushing manufacturer). If the tanδ value after this treatment is restored to a normal value – than the bushing can be used. The drying process can be repeated once again and if, after this second treatment, tanδ does not reach normal values – the bushing should be replaced with a new one.

In most cases, the oil end of the resin impregnated synthetic (RIS) bushing also needs to be protected from UV radiation. Since the synthetic layers are non-hygroscopic and are not close to the surface, the issue of moisture absorption is greatly reduced or eliminated completely. However, this property is still not proven in long-term practice (RIS is a new technology) and certain storage precautions can be recommended.

Insect protection is primarily for bushings with a central tube such as draw lead and draw rod bushings. It is recommended to block this central tube with preferably inorganic material, as insects tend to take up residency in this area.

All gasket materials are aged by UV radiation and ozone to some extent, but when a bushing is not installed, it can be more vulnerable to gasket degradation because of the exposure of the inboard end and/or the orientation of the bushing. If the bushing is stored in direct sunlight or in an ozone rich environment, the protection of the gaskets and polymeric materials of the bushing is recommended.

Modern silicone rubber sheds on any type of bushing are very durable but have some storage considerations. If the bushing is stored for long periods of time while being supported by the rubber sheds, the sheds can be damaged.

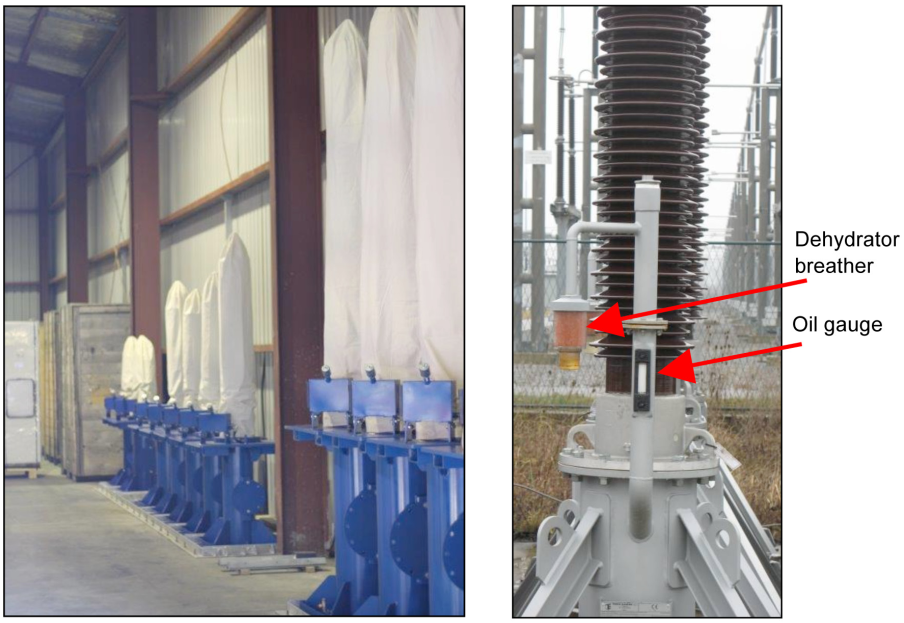


Figure 6.2: Example of RBP and RIP bushing long-term storage (left: New Zealand experience, right Croatian experience)

Figure 6.3: Example of long-term storage of various bushing types, [3.2.8]

Silicon rubber sheds are attractive to birds, rodents, monkeys, etc. [3.2.8], [6.1], even though the rubber has no nutritional value, Figures 6.4. and 6.5. They pick or chew the rubber and damage the bushing when the bushing is not in service (recent information shows that it can also happen in service, refer to section 4.1.4.). Therefore, they should be stored where they are protected from these pests. Experience from one 400 kV substation in Central Europe shows that silicone rubber sheds were “eaten” by rodents up to a level that the creepage path was seriously jeopardized, Figure 6.5. This occurred after about 10 years of indoor storage in their original package, wrapped in plastic foil.

The development of silicone bushing upper envelope sheds resistant to animal attack is recommended, but in an ecologically acceptable way. In some countries this is a serious problem, both in storage and in service.

Figure 6.4: Example of rodent attack on the silicone sheds [6.1]

Figure 6.5: Example of rodent attack on the silicone sheds after 10 years storage in the original package (marked with red arrows)

For RBP and RIP bushings with an uncontrolled (not graded) test tap C_2 capacitance, the surface absorption of moisture while exposed to ambient air during storage will elevate the tanδ_2 (PF). This is typically not an issue but may generate unnecessary concern regarding the bushing's suitability for service. If a controlled (graded) C_1 or a C_2 capacitance elevate tanδ_1 or a tanδ_2 (PF), it is recommended to contact the manufacturer for instructions.

During storage, bushing capacitance and tanδ as well as storage tank oil moisture content and breakdown voltage measurement is recommended in four years intervals. The dehydrating breather should be checked regularly. After storage and before the bushing is installed on transformer, capacitance and related tanδ measurement is recommended to prove the quality of bushing after storage. Values should be similar to those before storage. Measurement recommendations are in sections 5.2.2.1 and 5.2.2.2. For RBP and RIP bushings after installing, it is recommended to allow the soak-time of a day or two before energizing the transformer, which helps surface moisture re-absorption.

7. Conclusion

Bushings are among the most frequent transformer failure cause. According to the data from various researches and electric power utilities, bushings cause from 5 to 50 % of the total number of transformer failures. In almost all international transformer failure studies bushings, as a failure cause, are ranked in third place among transformer parts, after windings and tap changers. Bushing failures are the most common cause of transformer fires resulting in huge collateral and ecological damages at the switchyard

The first bushings were a kind of solid type of bushing often made from porcelain with an inserted conductor. Similar bushings are still used for distribution voltages because of their simplicity, reliability and low price. For higher voltages, condenser type bushings are used. One of the oldest capacitive graded bushing descriptions is dated back to 1906 and shortly after that the production of RBP bushings started. OIP technology was established in about 1944 to fulfil the needs for higher voltages and a lower PD level. In 1963, first OIP 500 kV bushing was introduced. Around 1950, the first RIP bushing was produced. Today, bushings are produced with rated voltages of up to 1200 kV AC and DC and with rated currents up to 35 kA. Around 1990, silicone sheds on glass fibre epoxy tube was introduced as an upper envelope instead of porcelain. Recent bushing developments are moving in the direction of silicone sheds applied directly on the RIP body and replacement of paper with inorganic material (RIS technology).

Two main fine electrical field grading technologies are used: with main electrodes only and with main and intermediate electrodes. Four main insulation technologies are used: RBP (obsolescent but still in production), OIP, RIP and RIS, as well as two main upper envelope types: porcelain and silicone (with or without epoxy tube). Three main current conduction path types are used: draw-lead, draw-rod and bottom-connected. The upper or lower part of the bushings are adapted mainly to oil, air or SF_6. The main advantage of RIP with a silicone/composite upper envelope compared to OIP with a porcelain upper envelope, are better transformer fire, earthquake and vandalism resistance. Despite that, the OIP bushing, as a well-known and established technology, still shares a significant part of the world market.

Condenser bushings for higher temperatures than 120 °C are unfortunately still not available on the market. Considering the fact that recently developed transformers with a higher temperature class of solid and liquid insulation may have a top oil temperature limit significantly higher than 120 °C, it can be recommended that bushings, for a service voltage ≥ 72,5 kV, for higher temperature should be developed.

Four questionnaires have been prepared, promoted and analysed. The key results are:

Q1 - Bushing in service failure: 240 in-service failures were collected on more than 101.000 of in-service bushings:

- 67 % of failures are incipient (98 % of outages are scheduled). 70 % of them result in a transformer outage duration lasting less than a week and only 5 % lasting more than a month. The transformer active part contamination isn't reported. The most abundant failure cause is a condenser body defect 53 %.
- 30 % of failures are terminal (73 % of outages are forced). 47 % of them have an outage duration lasting more than a month. The visual appearance of a failed bushings is 71 % mechanical damage (11 % with projection of the upper envelope debris). In 30 % of cases, the transformer active part is contaminated with bushings debris. Failure causes are seismic activity 18 %, followed by condenser body defect 12 %, moisture ingress 9 % and overvoltage 7 %.
- Failure rates show an increasing trend with rated voltage. RBP bushings have a substantially higher failure rate that OIP and RIP (probably because of their age). The most "effective" diagnostic method which indicates failure is tanδ or PF in 45 % of the cases followed by visual inspection in 28 % of the cases.

Q2 - Bushing failure during transformer acceptance test (TAT): 99 bushing failures during TAT were collected among about 44.000 bushings. Based on the whole population bushing TAT failure rate is 0,23 %. It increases with rated voltage.

- Failure appears during PD test 36 %, followed by AC withstand voltage test 30 % and LI full wave 10 %. 82 % of failures appear during dielectric tests.

- Remedial work duration is a day to a week in 44 %, followed by more than a month in 39 % of cases.
- Failure cause is a condenser body defect 23 %, followed by lower housing defect 12 %, oil leak 9 % and end shield problems 5 %.

Q4 - Bushing diagnostics, maintenance and failure practice: 31 responses from utilities were received.

- 52 % of utilities apply periodic (off-line) diagnostic methods, 45 % of utilities apply both continuous and periodic diagnostic methods. No cases of applying only continuous (on-line) methods.
- Most often used off-line (periodic) diagnostic methods are capacitance and tanδ or PF measurement 97 %, followed by IR 77 % and DGA 53 %.
- Most often used on-line (continuous) diagnostic methods are capacitance, 93 %, followed by tanδ or PF 64 % and voltage transients 21 %.
- Most often used decision criteria for capacitance change is 5 %, and for tanδ or PF the limit is up to 1 % for OIP and RIP and up to 2,5 % for RBP.

The results clearly reveal that bushing periodic and continuous diagnostics helps in the prevention of bushing terminal failures and consequently, transformer failure. Developed questionnaires can be guidelines for future research of that kind.

Based on the bushing failure mechanisms and related case studies, the following recommendations can be proposed:

- A flexible bushing connection to the switchyard is recommended.
- A draw-lead should be properly insulated from bushing central tube.
- A thick resin coated bushing end shield should be tested as a part of the bushing's internal insulation.
- If bushing obstacle (barrier) to wind or snow is used, it should protect entire bushing length. Bushing partial obstacle should be avoided.
- For long bushings, an axially-shifting paper overlap is recommended.

Failure case studies explained in this brochure are gathered thorough WG members, experience and references. Hopefully they are representative for the worldwide bushing population.

Bushing periodic and continuous monitoring related recommendations are:

- The change of bushing capacitance that corresponds to short-circuited adjacent electrodes should be stated in the bushing's technical data. If this is not convenient, the bushing manufacturer should suggest the allowable capacitance change. For periodic capacitance measurement, it can be suggested that the bushing should be replaced when the capacitance change reaches this value.
- For continuous capacitance measurement, it can be suggested that the bushing should be replaced when the capacitance change reaches twice the value that corresponds to short-circuited adjacent electrodes. The change of bushing capacitance that corresponds to short-circuited adjacent electrodes can be used as an alarm value.
- Bushing capacitance and tanδ or PF temperature conversion should be defined by the bushing manufacturer.
- Test tap continuous operating voltage and design value of lighting impulse withstand voltage should be stated in the bushing's technical data.
- The quantity of oil that can be allowed to be extracted for an oil sample from OIP bushing without topping-up, should be stated in the bushing's technical data.
- To allow topping-up of the oil, the insulation oil (liquid) type used in the bushing should be stated in the bushing's technical data.
- Standardization of the test tap design is recommended.

Bushing storage related recommendations are:

- If a RBP bushing that has already been in service is to be re-installed again, vacuum treatment is recommended (contact bushing manufacturer).
- Development of silicone bushing upper envelope sheds resistant to animal attack is recommended.

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Annex 1. Q1 - Bushing in-service failure questionnaire

CIGRE WG A2-43: Transformer Bushings Reliability

Bushing failure questionnaires (≥ 72.5 kV)

General Guide

Four questionnaires have been prepared by CIGRE WG A2.43 - Transformer bushings reliability, TF 1 - Bushing failure rate

Q1: Bushing in service failure questionnaire - for utilities and/or transformer owners. Main goals are: obtaining bushing failure rate and collecting relevant facts about bushing failure for statistical purposes. For each bushing failure in service (incipient or terminal) a row in *Failure Data* sheet should be filled.

Q2: Transformer Acceptance Test (TAT) failure questionnaire for bushings - for transformer manufacturers. Main goals are: obtaining TAT bushing failure rate and collecting TAT bushing failures relevant facts for statistical purposes. For each TAT bushing failure a row in *Failure Data* sheet should be filled.

Q3: Bushing manufacturer failure data questionnaire – for bushing manufacturers. Main tasks are: obtaining bushing failure rate from bushing manufacturer quality records data. Each bushing manufacturer should fill a row with requested data in *Failure Data* sheet

Q4: Bushing diagnostics, maintenance and failure practice questionnaire - for utilities and/or transformer owners. Main tasks are: collecting relevant facts about utilities/transformer owners bushing diagnostics practice (periodic and continuous), bushing maintenance and failure records practice.

Notes.

- Before filling any data please read sheet: *Definitions*
- For accurate failure rate calculation it is very important that all the bushing failures on a certain bushing population in the reference period should be counted
- Q1 - Bushing population - If a utility already has the population of bushing in service documented this data may be used, if not, bushing population should be counted from transformer population, see sheets *Population Data* and *Population Example*
- Q2 - Bushings population represents the number of used bushing in the reference period
- Q3 - Bushings population represents the number of manufactured bushings in the reference period
- Diagnostics methods can be used in two different ways: on-line (continuous, continuous monitoring) implies that transformer is energized and off-line (periodic) implies that transformer can be deenergized or energized (i.e during periodic IR scaning, PD testing, etc.)
- Because of simplicity, understability and easier statistical evaluation drop down lists are frequently used in the questionnaires
- Please answer as many questions as possible. If the answer is unknown to participants use *Unknown* in the drop down list or simply write *Unknown.* This information is also very important

Note:
General Guide is same for all four questionnaires

Q1 - Bushing in service failure questionnaire (≥ 72.5 kV)

Definitions & Remarks

Incipient bushing failure	Incipient bushing failure is a bushing's partial lack of performance which could develop into a terminal bushing failure. It is recognised either by visual inspection (surface cracks, oil leaks) or by a diagnostic method and it can be prevented by bushing replacement or repair, usually with no consequences for the transformer and in a relatively short period of time (≤ 7 days).
Terminal bushing failure	Terminal bushing failure is an instantaneous loss of bushing service ability.It is usually a bushing "rupture" or "collapse" that often causes huge damage to the transformer.
Transformer acceptance test (TAT) bushing failure	TAT bushing failure occured if a new transformer failed the acceptance test at the factory or at site during pre-livening checks because of the bushing. The bushing would be replaced or repaired before the next transformer acceptance test.
Failure with forced outage	Regarding bushings, in most cases it is a trip activated by transformer protection (or manually tripped due to an alarm within 30 min). Forced outage is often related to bushing terminal failure.
Failure with scheduled outage	Regarding bushings, in most cases it is a transformer taken out of service by staff in a planned manner i.e. more than 30 min from first noticable effect. Scheduled outage is often related to bushing incipient failure .

Population Data:

1	**Reference Period**	Period when failures are counted (i.e. 01. January 2000. to 31. December 2010.) The reference period for failures
2	**Bushings in Service**	Bushings installed on operational transformers. This should include bushings installed on operational spare transformers but should exclude bushings stored as spares. Neutral bushings are not counted
4	**Population information**	See 'population example' sheet tab for simple example of how to fill out the total population of bushings spreadsheet

Failure Data:

1 - Identification of the Bushing

1.2	**Rated Voltage**	Rated phase to phase voltage of the bushing
1.4	**Bushing Application**	The defintion of HVDC-AC and HVDC-DC bushings is as follows: HVDC-AC = bushings for combined voltage application i.e. bushings on the valve side of converter transformers. HVDC-DC = bushings for pure DC application i.e. bushings on series reactors on high voltage side of DC converter valve
1.6	**Insulation System Type**	OIP (Oil Impregnated Paper), RIP (Resin Impregnated Paper), RBP (Resin Bonded Paper), ST (solid type), OT (other), UT (unknown type)
1.7	**Upper Housing (Outer Envelope)**	The external insulation material of the bushing upper housing (i.e. above the flange).
1.8	**Lower Housing (Inner Envelope)**	The external insulation material of the bushing lower housing (i.e. below the flange)
1.9	**Connection Type**	**Draw-lead system**: a bushing with this system uses a **current carrying** draw-lead or solid-rod conductor drawn through the hollow tube and enabling its connection to the top terminal. **Draw-rod system**: a bushing with this system uses a **non-current carrying** rod drawn through the hollow tube and enabling a connection between the bushing's inboard end terminal and the transformer or reactor winding lead. **Bottom connection system (non removable conductor)**: a bushing with this system uses a current carrying solid rod which is non removable and enables a connection between the bushing's inboard end terminal and the transformer or reactor winding lead.

2 - Features of the Transformer (this could be a Reactor or other such device)

2.1	**Transformer Rated Power**	The maximum nameplate rated power with most effective cooling
2.2	**Transformer Rated Voltage**	Rated phase to phase voltage of the transformer

3 - Detail of Failure Occurence

3.2	**Service Years to Failure**	Number of years the bushing was in operational service before failure

4 - Bushing Failure Data

4.1	**Relevant Environmental Conditions**	Please detail any unusual environmental conditions which may have contributed to the failure of the bushing i.e. high salt pollution, heavy rain, ….

5 - Diagnostic Data of Bushing

Detail of diagnostics performed on failed bushing prior to failure

CIGRE WG A2.43: Transformer bushings realiability

Q1 - Bushing in service failure questionnaire (≥ 72.5 kV)
Population data

1	**REFERENCE PERIOD (From 01 January 2000 only or later)**	
2	**UTILITY INFORMATION** Country Utility Name Mailing Address Contact Person Telephone Number Fax Number Email Address	
3	**FAILURE DATA COLLECTION** **Please describe how bushing failure data is collected in your utility.**	
3,1	**Existence of terminal bushings failure database**	
3,2	**Existence of incipient bushings failure database**	
4	**BUSHINGS POPULATION INFORMATION: Bushings in servce are counted - see sheet "Definitions"**	

Tr. nominal voltages X/Y/Z	No. of identical Tr. 1)	Years in service in ref. Period	**Number of line2) bushings per voltage and insulation type**							**Remarks**
			69≤U<100	100≤U<200	200≤U<300	300≤U<500	500≤U<700	U≥700	HVDC (all voltages)	
SUM (total, per insulation type, per voltage)										

Notes and explanations:

Particular utility, transformer and bushing manufacturer information and failure data are confidental. Only summary/consolidated data will be published
Bushings population is evaluated fom transformer population, see detailed explanation in sheet "Population example"

Q1 - Bushing in service failure questionnaire (≥ 72.5 kV)
Bushing population evaluation (example)

Tr. nominal voltages X/Y/Z	No. of identical Tr. 1)	Years in service in ref. Period	**Number of line2) bushings per voltage and insulation type**							**Remarks (data description)**
			69≤U<100	100≤U<200	200≤U<300	300≤U<500	500≤U<700	U≥700	HVDC (all voltages)	
220/110/35	5	10		OIP 3	RBP 3					Transformer or autotransformer, 3 phase unit (3 OIP 110 kV bushings and 3 RBP 220 kV bushings), 5 identical transformers, 10 years in operation in ref. period
220/110/35	2	7		OIP 3	RBP 3					Transformer or autotransformer, 3 phase unit
220/√3/110/√3/35	3	2		OIP 1	RBP 1					Single phase line-ground transformer (or autotransformer)
145/25	1	8		OIP 2						Single phase line-line transformer
115/35/11	10	10		UT 3						Unknown type of bushings, 3 phase unit
400/400/20	2	8				OIP 6				Phase shifter - 3 phase unit
400	1	5				RIP 6				Series reactor, 3 phase unit
400	3	2				RIP 2				Series reactor, single phase unit
220	1	5			OIP 3					Shunt reactor, 3 phase unit
220	3	4			OIP 1					Shunt reactor, single phase unit
300/√3/173/100	3	3				RIP 1			RIP 4	Single phase HVDC transformer, two valve windings
400/220/11 3)	1	3			OIP 3	RIP 3				
400/220/11 3)	1	2			OIP 3	RIP 2				3 phase transformer, 5 y in service in ref. period. After 3 y one RIP bushing replaced with OIP
400/220/11 3)	1	2				OIP 1				
750/400/15	2	3				RIP 3		OIP 3		Autotransformer, 3 phase unit, 2 identical transformers, 3 years in service in ref. Period
SUM (total, per insulation type, per voltage)										

Notes and explanations:

Bushing insulation type: RBP, OIP, RIP, ST (solid type), OT (other), UT (unknown type)

AC and HVDC bushings should be considered separately

Number of bushing service years (per voltage and insulation type) for certain transformer: No. of identical Tr. x Years in service in ref. Period x Number of line bushings per voltage and insulation type

1) **Identical transformers (with reference to voltage class arrangement):** same number bushings and their insulation system types; same number of years in operation in ref. period

2) **Neutral bushings are not counted**

3) **Example of bushing counting in the case when bushing type changed in reference period**

Line bushing counting explanations:
- Bushing counting examples for often used transformer types are shown in the table
- For same nominal voltage, 3 phase transformer (with separate windings) and 3 phase autotransformer have same number of bushings
- Single phase transformer two types: connection between line and neutral (ground) and connection between lines (often used for railways supply)
- HVDC transformers: usually single phase transformers with one or two valve windings. For other types - see transformer data

Q1 - Bushing in service failure questionnaire (≥ 72.5 kV)

Failure data

No.	1 - IDENTIFICATION OF THE BUSHING											2 - FEATURES OF THE TRANSFORMER (OR REACTOR ETC)		
	1.1 Lightning Impulse Voltage [kV]	1.2 Rated Phase-Phase Voltage [kV]	1.3 Nominal Current [A]	1.4 Bushing Application	1.5 Bushing Type	1.6 Insulation System Type	1.7 Upper Housing (Outer Envelope)	1.8 Lower Housing (Inner Envelope)	1.9 Connection Type	1.10 Year of Manufacturing	1.11 Bushing manufacturing standard and year	2.1 Transformer Rated Power [MVA]	2.2 Transformer Rated Phase-Phase Voltage [kV]	2.3 Transformer Application
				AC	Oil-air	OIP	Porcelain	Porcelain	Draw lead system					Substation transformer
				HVDC - AC	Oil-oil	RIP	Silicone rubber	Epoxy	Draw rod system					Auto transformer
				HVDC - DC	Oil-SF6	RBP	Unknown	Unknown	Bottom connection system					Power Station- Generator step-up
					SF6-air	Solid type	Other	Other	Unknown					Power Station- Unit transformer
					Other	Unknown type		None						HVDC - transformer
						Other								Phase Shifting transformer
														Series Reactor
														Shunt reactor
														Other

3 - DETAIL OF FAILURE OCCURENCE		4 - BUSHING FAILURE DATA										
3.1 Year of Failure	3.2 Years of Service Prior to Failure	4.1 Relevant Environmental Condtions	4.2 Type of Outage	4.3 Outage Duration	4.4 Type of Bushing Failure	4.5 Appearance on Transformer	4.6 Appearance on Bushing	4.7 Internal Breakdown of Bushing	4.8 Flashover External to Bushing	4.9 Transformer active part contaminated with bushing debris	4.10 Failure cause/origin	4.11 Investigation after failure (post mortem) performed
			Forced	Less than a day	Incipient	None	None	None	None	Yes	Over Voltage	Yes
			Scheduled	A day to a week	Terminal	Oil leak	Leak	Upper axial flashover	Upper	No	Current Overloading	No
				A week to a month		Rupture	Collapse	Lower axial flashover	Lower		Overheated Connections	
				More than a month		Fire	Upper envelope damage	Radial puncture			Bushing Overheating	
						Other	Lower bushing part damage				Short Circuit Dynamic Stress	
							Contact damage-overheating				Seismic Activity	
							Mechanical damage				Cantilever Damage	
							Voltage or test tap damage				Animal Encounter	
							Upper envelope blown up (with projection of pieces)				Vandalism/Impact Damage	
							Other				Condenser Body Defect	
											Upper housing defect	
											Lower Housing Defect	
											End Shield Problems	
											Loss of Tap Connection - Internal	
											Loss of Tap Connection - External	
											Oil leak	
											Moisture Ingress	
											Corrosive Sulfur	
											Other Internal Contamination	
											External Contamination	
											Corrosion	
											Improper Mounting	
											Improper Maintenance	
											Improper Storage	
											Improper Transport	

5 - DIAGNOSTIC DATA OF BUSHING (performed prior to failure)				
5.1 Visual Inspection	5.2 Diagnostic Methods Applied	5.3 Frequency of Off-line Diagnostic Methods	5.4 Most Recent Measurement [year]	5.5 Method which indicated incipient failure
Monthly	On line (continuous)	Monthly		Capacitance
6 monthly	Off line (periodic)	6 monthly		Tan δ or PF
Yearly	Both	Yearly		Tand or PF FDS (Frequency Domain Spectrum)
1 to 2 years	None	1 to 2 years		PDC (Polarization - Depolarization Current)
2 to 4 years		2 to 4 years		RVM (Recovery Voltage Measurement)
4 to 8 years		4 to 8 years		Conductive resistance
More than 8 years		More than 8 years		Insulation resistance
				Infra red (IR) scanning
				DGA
				Moisture analysis
				Creepage current
				Partial discharge test
				Oil pressure
				Transients measurement
				Visual inspection

Annex 2. Q2 - Transformer Acceptance Test (TAT) bushings failure questionnaire

Q2 - Transformer Acceptance Test (TAT) bushings failure questionnaire		
Definitions, Remarks		
	Incipient bushing failure	Incipient bushing failure is a bushing's partial lack of performance which could develop into a terminal bushing failure. It is recognised either by visual inspection (surface cracks, oil leaks) or by a diagnostic method and it can be prevented by bushing replacement or repair, usually with no consequences for the transformer and in a relatively short period of time (≤ 7 days).
	Terminal bushing failure	Terminal bushing failure is an instantaneous loss of bushing service ability.It is usually a bushing "rupture" or "collapse" that often causes huge damage to the transformer.
	Transformer acceptance test (TAT) bushing failure	TAT bushing failure occured if a new transformer failed the acceptance test at the factory or at site during pre-livening checks because of the bushing. The bushing would be replaced or repaired before the next transformer acceptance test.
Population Data:		
1	**Reference Period**	Period when failures are counted (i.e. 01. January 2000. to 31. ecember 2010.) The reference period for failures should be from 01 January 2000. If a utility only has data from a later date i.e. 2004 then this date should be detailed in the questionnaire. The period should not be shorter than 5 years and no longer than 12 years..
Failure Data:		
1 - Identification of the Bushing		
1.2	**Rated Voltage**	Rated phase to phase voltage of the bushing
1.4	**Bushing Application**	The defintion of HVDC-AC and HVDC-DC bushings is as follows: HVDC-AC = bushings for combined voltage application i.e. bushings on the valve side of converter transformers. HVDC-DC = bushings for pure DC application i.e. bushings on series reactors on high voltage side of DC converter valve
1.6	**Insulation System Type**	OIP (Oil Impregnated Paper), RIP (Resin Impregnated Paper), RBP (Resin Bonded Paper), ST (solid type), OT (other), UT (unknown type)
1.7	**Upper Housing (Outer Envelope)**	The external insulation material of the bushing upper housing (i.e. above the flange).
1.8	**Lower Housing (Inner Envelope)**	The external insulation material of the bushing lower housing (i.e. below the flange)
1.9	**Connection Type**	**Draw-lead system**: a bushing with this system uses a **current carrying** draw-lead or solid-rod conductor drawn through the hollow tube and enabling its connection to the top terminal.
		Draw-rod system: a bushing with this system uses a **non-current carrying** rod drawn through the hollow tube and enabling a connection between the bushing's inboard end terminal and the transformer or reactor winding lead.
		Bottom connection system (non removable conductor): a bushing with this system uses a current carrying solid rod which is non removable and enables a connection between the bushing's inboard end terminal and the transformer or reactor winding lead.
2 - Features of the Transformer (this could be a Reactor or other such device)		
2.1	**Transformer Rated Power**	The maximum nameplate rated power with most effective cooling
2.2	**Transformer Rated Voltage**	Rated phase to phase voltage of the transformer

Note:
For General Guide see Annex 1.

CIGRE WG A2-43: Transformer bushings reliability

Q2 - Transformer Acceptance Test (TAT) failure questionnaire for bushings (≥ 72.5 kV)

1.	**REFERENCE PERIOD (From 01 January 2000 only or later)**							
2	**COMPANY INFORMATION** Country Transformer Manufacturer Name Mailing Address Contact Person Telephone Number Fax Number Email Address							
3	**POPULATION INFORMATION** *Please indicate the number of bushings per voltage used during the reference period. Bushings used only for transformer testing are not counted.*	**Rated Phase-Phase Voltage [kV]**						
		69 ≤ U <100	**100 ≤ U < 200**	**200 ≤ U < 300**	**300 ≤ U < 500**	**500 ≤ U < 700**	**U ≥ 700**	**HVDC (All voltages)**
3.1.	**OIP**							
3.2.	**RIP**							
3.3.	**RBP**							
3.4.	**Solid type**							
3.5.	**Others**							
4	**FAILURE DATA COLLECTION**							
4.1.	**Existence of TAT bushing failure database**							
5	**TAT failure rate: failed bushings/used bushings**							

Particular utility, transformer and bushing manufacturer information and failure data are confidental. Only summary/consolidated data will be published

Drop-down list for question 4.1.
Yes by bushing manufacturer
Yes by transformer manufacturer
No

Q2 - Transformer Acceptance Test (TAT) failure questionnaire for bushings (≥ 72.5 kV)

Failure data

	1 - IDENTIFICATION OF THE BUSHING										**2 - FEATURES OF THE TRANSFORMER (OR REACTOR ETC)**	
No.	1.1 **Lightning Impulse Voltage [kV]**	1.2 **Rated Phase-Phase Voltage [kV]**	1.3 **Nominal Current [A]**	1.4 **Bushing Application**	1.5 **Bushing Type**	1.6 **Insulation System Type**	1.7 **Upper Housing (Outer Envelope)**	1.8 **Lower Housing (Inner Envelope)**	1.9 **Connection Type**	1.10 **Year of Manufacture**	2.1 **Transformer Rated Power [MVA]**	2.2 **Transformer Application**
				AC	Oil-air	OIP	Porcelain	Porcelain	Draw lead system			Substation transformer
				HVDC - AC	Oil-oil	RIP	Silicone	Epoxy	Draw rod system			Auto transformer
				HVDC - DC	Oil-SF6	RBP	Unknown	Unknown	Bottom connection system			Power Station- Generator step-up
					SF6-air	Solid type	Other	None	Other			Power Station- Unit transformer
					SF6-SF6	Unknown type		Other				HVDC - transformer
					Other	Other						Phase Shifting transformer
												Series Reactor
												Shunt reactor
												Other

3 - BUSHING FAILURE DATA							
3.1 **Bushing failed which test during transformer factory testing?**	3.2 **Was this test previously performed**	3.3 **Appearance on Bushing**	3.4 **Breakdown Internal to Bushing**	3.5 **Breakdown External to Bushing**	3.6 **Transformer active part contaminated with bushing debris**	3.7 **Failure cause/origin**	3.8 **Remedial work duration**
Dielectric tests - LI Full	Yes by bushing manufacturer	None	None	None	Yes	Overheated Connections	Less than a day
Dielectric tests - LI Chopped	Yes by transformer manufacturer	Leak	Upper axial flashover	Upper	No	Bushing Overheating	A day to a week
Dielectric tests - SI	No	Collapse (rupture)	Lower axial flashover	Lower		Short Circuit Dynamic Stress	A week to a month
Dielectic tests - AC withstand		Upper envelope damage	Radial puncture			Condenser Body Defect	More than a month
Dielectric tests - PD		Lower bushing part damage				Upper housing defect	
Dielectric tests - DC		Contact damage-overheating				Lower Housing Defect	
Dilectrci tests - DCPR		Mechanical damage				End Shield Problems	
Heat run test		Voltage or test tap damage				Loss of Tap Connection - Internal	
Short circuit test						Loss of Tap Connection - External	
Transformer oil leakage test						Oil leak	
Other						Moisture Ingress	
						Corrosive Sulfur	
						Other Internal Contamination	
						External Contamination	
						Improper Mounting	
						Improper Storage	
						Improper Transport	
						Unknown	
						Other	

Annex 3. Q3 - Bushing manufacturer failure data questionnaire

Q3 - Bushing manufacturer failure data questionnaire (≥ 72.5 kV)	
Definitions, Remarks	
Incipient bushing failure	Incipient bushing failure is a bushing's partial lack of performance which could develop into a terminal bushing failure. It is recognised either by visual inspection (surface cracks, oil leaks) or by a diagnostic method and it can be prevented by bushing replacement or repair, usually with no consequences for the transformer and in a relatively short period of time (≤ 7 days).
Terminal bushing failure	Terminal bushing failure is an instantaneous loss of bushing service ability.It is usually a bushing "rupture" or "collapse" that often causes huge damage to the transformer.
Transformer acceptance test (TAT) bushing failure	TAT bushing failure occured if a new transformer failed the acceptance test at the factory or at site during pre-livening checks because of the bushing. The bushing would be replaced or repaired before the next transformer acceptance test.
Reference Period	Period when failures are counted (i.e. 01. January 2000. to 31. ecember 2010.) The reference period for failures should be from 01 January 2000. If a utility only has data from a later date i.e. 2004 then this date should be detailed in the questionnaire. The period should not be shorter than 5 years and no longer than 12 years.
Bushing failure rate (suggested method for calculation)	Number of bushing failures in reference period / Number of bushing service-years in reference period *Note - Bushing should have been be produced and failed within reference period*

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Q3 - Bushing manufacturer failure data questionnaire (≥ 72.5 kV)

This survey is for in service failure data (incipient and terminal) of bushings manufactured and failed within the defined reference period and should not include any failure of a bushing at the bushing manufacturer's premises

REFERENCE PERIOD (From 01 January 2000 only or later)	
Country	
Bushing Manufacturer Name	
Mailing Address	
Contact Person	
Telephone Number	
Fax Number	
Email Address	

No.	1 - AC bushings: Total quantity				2 - AC Bushing failure rate				3 - HVDC bushings: Total quantity				4 - HVDC bushing failure rate			
	1.1 RBP	1.2 OIP	1.3 RIP	1.5 Other	2.1 RBP	2.2 OIP	2.3 RIP	2.5 Other	3.1 RBP	3.2 OIP	3.3 RIP	3.5 Other	4.1 RBP	4.2 OIP	4.3 RIP	4.5 Other
1																

5 - DIAGNOSTIC DATA		6 - FAILURE RATE METHOD USED	7 - FAILURE INFORMATION
5.1 **Bushing storage and maintenance guide provided to the customer**	5.2 **Bushing diagnosis guide provided to the customer**	*Please write a short explanation about failure rate method used. Please note fact if failure data include or exclude transformer acceptance tests bushing failure (in the case when TAT cannot be extracted from qality data reccords)*	*Please provide information on most often failure mechanism/ cause, if known*

Drop-down list for questions 5.1, 5.2
Yes
On request
No

Annex 4. Q4 - Bushing diagnostics, maintenance and failure practice questionnaire

CIGRE WG A2-43: Transformer bushings reliability

Q4 - Bushings diagnostics, maintenance and failure practice questionnaire

1 UTILITY INFORMATION

Country
Utility/Company Name
Mailing Address
Contact Person
Telephone Number
Fax Number
Email Address

2 GENERAL DATA

2.1. Maximum system voltage in utility/company (KV)

2.2. Maximum transformer rated power in utility/company (MVA)

	Rated Phase-Phase Voltage [kV]					
	69 ≤ U <100	100 ≤ U < 200	200 ≤ U < 300	300 ≤ U < 500	500 ≤ U < 700	U ≥ 700
2.3. Average transformer rated power per voltage range in utility/company (estimation)						

2.4. Diagnostic measurements staff

3 DIAGNOSTIC/MAINTENANCE DATA

3.1. Existence of terminal bushings failure database

3.2. Existence of incipient bushings failure database

3.3. Bushing diagnostic methods applied

		Rated Phase-Phase Voltage [kV]						
	Please use drop down lists for each voltage class	69 ≤ U <100	100 ≤ U < 200	200 ≤ U < 300	300 ≤ U < 500	500 ≤ U < 700	U ≥ 700	HVDC (all voltages)
3.4.	**Bushing visual inspection interval** (for example: oil level/leak checking, upper housing checks…)							
3.5.	**On-line (continuous) bushing diagnostic methods used:**							
a)	Capacitance							
b)	Tan δ or PF							
c)	Creepage current							
d)	Oil pressure							
e)	Transients measurement							
f)	Partial discharge test							
g)	Other (please specify)							
3.6.	**Off-line (periodic) bushing diagnostic methods used:**							
a)	Capacitance							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
b)	Tanδ or PF (50 or 60 Hz)							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
c)	Tan or PF FDS (Frequency Domain Spectrum)							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
d)	PDC (Polarization - Depolarization Current)							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
e)	RVM (Recovery Voltage Measurement)							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
d)	Partial discharge							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
g)	Conductive resistance							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
h)	Insulation resistance							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
i)	Infra red (IR) scanning							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
j)	DGA							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
k)	*Moisture in the oil*							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
l)	Other (please specify)							
	Time between test (frequency of test)							
	Insert comment if different off-line periods completed for different bushing types							
3.7.	**Acceptable trend criteria for change in Capacitance (%):**							
a)	Please provide acceptable trend criteria for change in Capacitance if used for RIP bushings							
b)	Please provide acceptable trend criteria for change in Capacitance if used for OIP bushings							
c)	Please provide acceptable trend criteria for change in Capacitance if used for RBP bushings							
3.8.	**Acceptable limit and/or trend criteria for Tanδ or PF:**							
a)	Please provide acceptable limit or trend criteria for Tan δ or PF if used for RIP bushings							
b)	Please provide acceptable limit or trend criteria for Tan δ or PF if used for OIP bushings							
c)	Please provide acceptable limit or trend criteria for Tan δ or PF if used for RBP bushings							
3.9.	**What do you think is the most reliable on-line (continuous) or off-line (periodic) test to detect bushing failures?**							

Particular utility, transformer and bushing manufacturer information and failure data are confidential. Only summary/consolidated data will be published

Drop-down list for question number								
2.1.	2.2.	2.4.	3.1., 3.2.	3.3.	3.4.	3.5. a) to f)	3.6. a) to k)	
69 ≤ U <100	Up to 63	Part of the company	Yes	None	Conditional only	Yes	Yes	Conditional only
100 ≤ U < 200	64 to 300	Outsorcing	No	On-line (continuous)	Monthly	No	No	Monthly
200 ≤ U < 300	More than 300	Other		Off-line (periodic)	6 monthly			6 monthly
300 ≤ U < 500				On-line and Off-line	Yearly			Yearly
500 ≤ U < 700					1 to 2 years			1 to 2 years
U ≥ 700					2 to 4 years			2 to 4 years
					4 to 8 years			4 to 8 years
					More than 8 years			More than 8 years

Annex 5. Recommended 50/60 Hz capacitance and tanδ limits for high voltage condenser type bushings

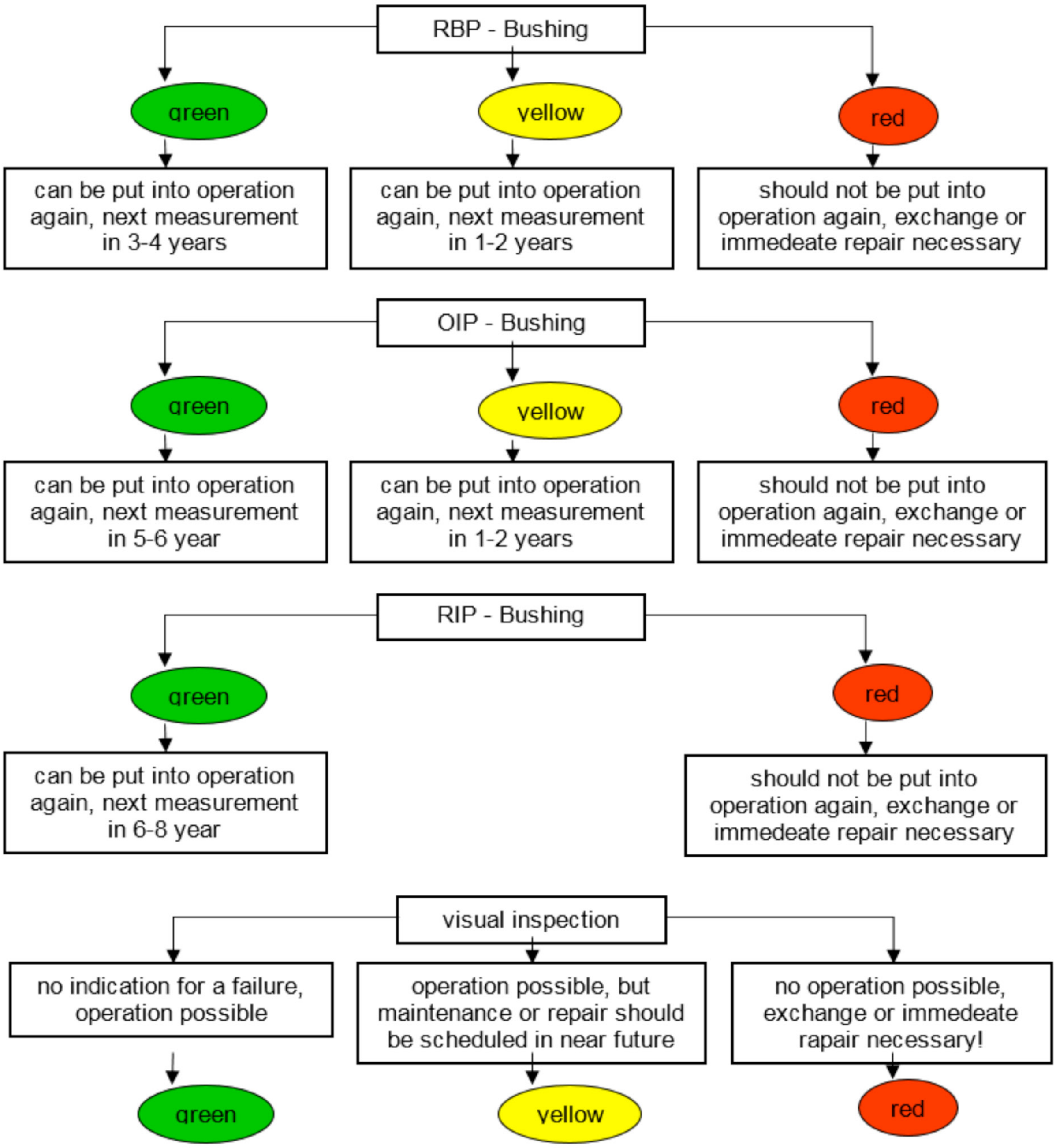

Figure A5.1: Flow chart for the assessment of high voltage bushings, part 1, [5.1]

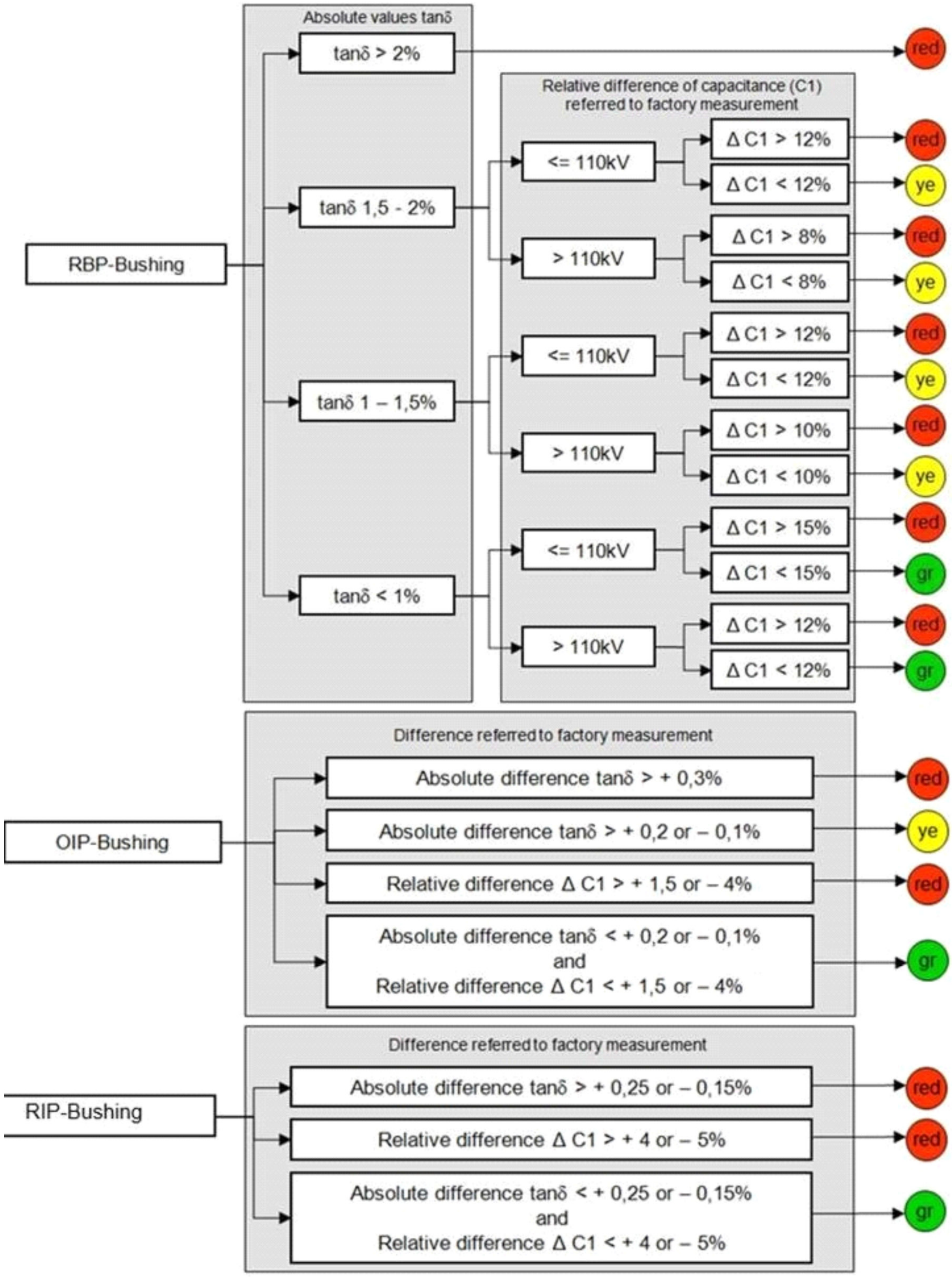

Figure A5.2: Flow chart for the assessment of high voltage bushings, part 2, [5.1]

General requirements for capacitance and tanδ measurements:

- The cables should be removed from the bushings.
- The bushings must have a measuring tap or must be mounted isolated from the transformer tank.
- If the bushings are mounted isolated from the transformer tank the resistance between bushing flange and transformer tank has to be higher than10 to 100 kΩ (depends on measurement method used, see chapter 5.4).
- The porcelain surface has to be dry and clean. To avoid effects from surface currents the porcelain surface should be cleaned with recommended cleaners, if necessary.
- Depending upon on the condition, also silicone rubber should be cleaned with recommended cleaners before a measurement is done.
- When the weather is foggy, with rain or snow no capacitance and tanδ measurements should be done. If measurement is urgent special measures should be applied.
- With bushing temperatures below 5 to 10 °C no capacitance and tanδ measurements should be done. If measurement is urgent special measures should be applied.
- Ladders, parts of scaffolds and packing crate can influence measurement results. If the results are questionable these influences should be considered.

The temperature of the insulation can affect the dissipation/power factor results. Temperature correction factors for OIP and RIP bushings are shown in Figure 5.2.2.2.1. The temperature of the bushing lies between the oil temperature of the transformer and the ambient temperature. The temperature of the oil and the ambient temperature should be recorded in the test report.

Leakage currents across the surface of the outer insulator (porcelain or silicone) may also have some influence, particularly if the surface is dirty and wet. In case of unexpectedly high dissipation/power factor values, the bushing should be cleaned before the measurement is repeated. For silicone composite bushings, the cleaning instructions of the manufacturer should be followed, because some cleaning chemicals can damage the silicone. Additionally, a collar which is connected to the guard circuit can be used to suppress the influence of the surface current.

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