Journal of Energy

VOLUME 61 Number 1–4 | 2012 Special Issue

journal homepage: http://journalofenergy.com/

Antun Mikulecky
Končar - Electrical Engineering Institute
amikul@koncar-institut.hr

# TRANSFORMER BUSHINGS – FAILURE CASE STUDIES

## SUMMARY

Relationship between bushing failure and transformer failure is discussed and, in regard of that, two bushing failure types are recognized: incipient bushing failure that does not result in transformer damage and terminal bushing failure having transformer failure as a consequence. It can be seen, that without applying the diagnostics, all bushing failures are terminal. Thirteen bushing failures have been analyzed regarding their cause, failure mechanism and consequences. In that sense, the ability and limitation of off line and on line diagnostics are discussed and some improvements are proposed. Some switchyard properties in the aspect of fire protection are indicated and, especially, the possible influence of rigid tubular connections on bushing failures. Beside mentioned design, service, condition diagnostics and other properties of all three condenser types of bushings are described in the paper.

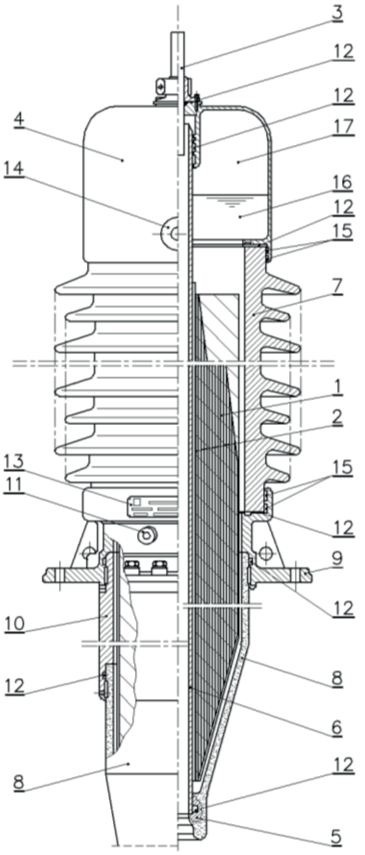
**Key words:** bushing, failure, power transformer, diagnostics, tubular connection, fire protection

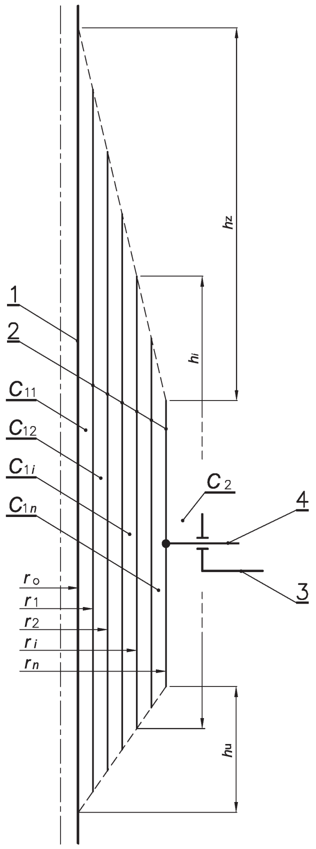
## 1. INTRODUCTION

Transformer bushing is a device through which the connection between the switchyard and the transformer winding is achieved, [1]. It conducts current and provides insulation to the tank. Bushing is positioned on the border of insulation media, usually oil on the lower side, and air, SF6 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 transformers. There are two main types of bushings used most frequently in the transformer technology: ceramic (porcelain) bushings, which are dominant at distribution voltages, and condenser type bushings, used for the past 50 years as the only choice for higher voltages. This paper deals with condenser type bushings. They are produced in three types of technology: RBP (resin bonded paper), OIP (oil impregnated paper), and RIP (resin impregnated paper), by wrapping on a central tube or conductor, with electrodes being inserted at certain diameters that grade radial and axial voltage stresses. A drawing of the oil – air OIP type condenser bushing is shown in Figure 1, and a schematic drawing of the bushing condenser body is shown in Figure 2.Condenser bodies, Figures 1 and 2 are schematically almost identical for all three bushing technologies, but their physical features differ. Condenser bodies of RBP and RIP represent solid products which are processed by turning. They mechanically adhere firmly and tightly to the flange (position 9 in Figure 1), so in this manner and with their integrity, they separate transformer oil from the surrounding medium. Therefore, the lower envelope (position 8 in Figure 1) is not necessary, because the body itself fulfills its task. In the case of condenser body breakdown (position 1), 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. This, then, 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 sealing effect of the condenser body to the flange, so in the

https://doi.org/10.37798/2012611-4249

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 to the flange and the sealing effect is preserved. (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; therefore, this version is significantly worse than the OIP bushing case in Figure 1).





Designations, Figure 1:
1 – Condenser body
2 – Electrodes
3 – HV connection
4 – Head
5 – Electrostatic screen
6 – Central tube
7 – Upper anvelope
8 – Lower anvelope
9 – Flange
10 – Flange extension
11 – Test tap
12 – Sealing
13 – Marking plate
14 – oil gauge
15 – Binding cement
16 – insulating oil
17 – Expansion space

Designations, Figure 2:
1 – Central tube
2 – Electrodes
3 – Flange
4 – Test tap
$C_{1i}$ – Capacitor, $i^{th}$ in line
$r_i$ – Radius of the $i^{th}$ electrode
$h_i$ – Height of the $i^{th}$ electrode
$h_z$ – Slope of the arial part
$h_u$ – Slope of the oil part
$C_1$ – Condenser body capacitance
$(1/C_1 = 1/C_{11} + \cdots + 1/C_{1i} + \cdots + 1/C_{1n})$
$C_2$ – Test tap capacitance

Figure 1: Drawing of the oil – air OIP type bushing

Figure 2: Bushing condenser body (schematically)

It is interesting to note that the shut-of valve, which serves the purpose of preventing oil leakage from the conserver in case of tank rupture, often does not fulfill its role, due to low oil flow when bushing failure occurs. Adjusting the shut-of valve to a lower flow may lead to transformer trip because its false activation is caused by the sudden cooling of the transformer. False shut-of valve activation leads to Buchholz relay activation without the action of any other protection relays. Upper oil – air bushing envelopes (position 7 in Fig. 1) contain sheds to ensure satisfactory creepage distance and are made of porcelain or composite materials, with silicone sheds, or, most recently, silicone sheds are applied directly on the RIP body. 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 insulation liquid. In RIP bushings, this space is filled with oil or with insulation foam for the completely dry construction, or the space does not exist if silicone sheds are applied directly onto the body. The porcelain upper envelopes are durable but breakable. They usually burst during bushing breakdown and are sensitive to vandalism. Their hydrophobicity is reduced in the polluted atmosphere. Composite upper envelopes, on the other hand, are mechanically tougher, more resistant to vandalism, they do not burst and their hydrophobicity is better, but they are less durable than the porcelain ones. RBP and, especially, 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 better seismic characteristics than OIP bushings, [2, 3]. RBP and RIP bushings can withstand temperatures up to 120 °C, whereas OIP bushings are resistant up to 105 °C. OIP and RIP bushings have a very low partial discharge (PD), regularly several pC at test voltages. RIP bushings are sensitive to the presence of PD because they have no possibility of regeneration that OIP ones have. Concerning this matter, RBP bushings have essentially poorer characteristics. Their PD reaches several hundred pC at test voltages and it can be even a hundred at operating voltage. The reason is that they always contain some air, so this technology is nowadays considered obsolete. Capacitance and tan$\delta$ for OIP and RIP bushings are permanent parameters until a disturbance occurs, making them very favorable for diagnostics. RBP bushings gradually increase capacitance during operation (even by ten or more %) due to oil impregnation and this can mask their defects.

## 2. BUSHING FAILURE DEFINITION

In the physical sense, failure occurs when service strength exceeds withstand strength of the material. Based on this, the definition widely accepted in engineering states that failure of a machine/device comprises the loss of functional properties resulting in termination of service. Repair or replacement is necessary before restarting. [4]. Partial loss of properties is referred to as defect. This definition of failure is based on the assumption that the device possesses bipolar functional features (functional properties exist – no failure and vice versa). The definition is clear, but more suitable for the device manufacturers than for the users. The users are more interested in the operational availability of the device. Namely, there are situations when a device is not operationally available, but there is no loss of functional properties. Characteristic situations of this kind are outages due to planned or unplanned condition diagnostics or for maintenance. In the sense of availability, every unplanned outage tends to be considered a failure. In this sense, a very interesting definition [5] states that failure presents any situation resulting in an unplanned outage for the purpose of investigation, repair or replacement. It takes into account the fact that condition monitoring by means of off line and on line diagnostics gives good results and has become the common practice of power utilities throughout the world. On the other hand, transformers can have more than ten bushings and failure of any one of them results in transformer failure. The second above mentioned definition is more appropriate for devices, whose condition is regularly diagnostically monitored, although it can, due to legal consequences, lead to intensive discussions between users and manufacturers. Defining the decision criteria when failure has been diagnosed by measurement but the device can still be in service, is a very delicate problem. This kind of decision criteria will not be well and impartially defined soon. It is interesting to note that decision criteria depend on whether diagnostics is periodical or continuous. An additional problem is that, according to this definition, very similar events may or may not be considered as bushing failure meaning that it is not unambiguous. The latter definition has another consequence: two types of bushing failures have to be recognized with respect to the failure impact on the transformer (or the power system). They can be named terminal and incipient failure. In the first case, complete loss of operational properties occurs while in the latter case, there is an initial defect that can evolve into a complete loss of service features during operation. Therefore, two types of bushing failures can be distinguished:

- ***Terminal bushing failure*** presents a complete loss of bushing service ability. This is usually a bushing explosion that causes great damages and transformer pollution as well as fires resulting in great collateral damage. Therefore, these are unplanned, forced outages [4] with large direct and indirect costs. The cause of an explosion is always breakdown: condenser body, upper or lower envelope.
- ***Incipient bushing failure*** occurs when a defect that can evolve into a terminal failure is detected by a diagnostic method. This type of failure can usually be fixed without serious consequences for the transformer and in a relatively short down-time; therefore, with low direct and indirect costs.

Considering the complete situation, bushing failures cannot be prevented by condition diagnostics (they are defined by bushing quality and service conditions), but the proportion of terminal to incipient bushing failures can be reduced, resulting in better service reliability and considerable cost reduction.

## 3. FAILURE CASE STUDIES

In this section, terminal and incipient bushing failures in the past twenty two years, in which author was involved, are described. Their ratio in this paper is not realistic because initial failures are often not even registered, especially if they are less severe and do not result in transformer down-time lasting more than a few days. Incipient failures occur, in fact, several times more often than terminal ones. Failure descriptions are metodized based on relevant data: about the transformer (type, voltage and power), voltage and type of bushing, age, mode of failure (incipient, terminal, fire outbreaks), type of connection, service specificities, weather conditions at the time of failure, previous diagnostic data, estimated cause, and the failure scenario.

## 3.1. 123 kV Bushing Failures

### 3.1.1. Case 1:

The lower envelope of an OIP type 123 kV bushing on a 150 MVA, 220/110 kV autotransformer, voltage, about 40 years old, exploded in the spring of 2006, during heavy rain, Figure 3. The hydrodynamic shock caused by bushing breakdown was very intense. The transformer tank was ruptured in several places so oil was leaking out. Most of the remaining bushings on the transformer were damaged (upper porcelain envelope damage and dislocation in relation to the head or flange occurred, followed by oil leakage from the bushing). The active part of the transformer was damaged to a great extent (the OLTC was destroyed, tap winding leads were damaged, etc.) and polluted so it had to be scrapped. The bushing was connected to the switchyard by rope.

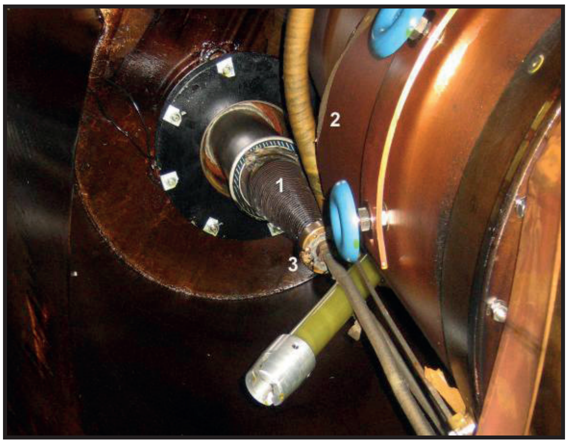


Figure 3: Exploded 123 kV bushing
(1 – lower part of the bushing without the exploded lower envelope,
2 – damaged diverter switch cylinder,
3 – electric arch traces on the lower electrostatic screen)

The transformer was regularly diagnostically tested in approximately four–year intervals. In the period between the last two measurements in the years 2002 and 2005, there was a relatively large increase of the bushing tan$\delta$ amounting to 41 %, but its value was still relatively low (0,52 %). The bushing was treated as suspicious and more frequent testing was recommended. A detailed inspection of the bushing debris was performed several months after the failure. The condenser body was unwounded but no traces pointing to the cause of failure were found. The lower part of the condenser body was clean, with no traces of an electric arch. Traces of an electric arch were found only on the lower porcelain envelope fragments that were collected from the transformer tank, flange and lower electrostatic screen.

The following failure scenario can be presumed. Weakening of the sealing system leads to a gradual moistening of the bushing insulation system resulting in an increase of tan$\delta$. Due to heavy rain and rapid cooling of the bushing, water can be sucked into it and this directly causes the lower envelope crepe breakdown (position 8 in Figure 1). Such a hydrodynamic shock breaks the OLTC diverter switch cylinder thus causing the loss of its axial support. Hence, the OLTC drops and moves to the side, deforming 123 kV line lead and on the tap winding leads in the process. Based on this case, it can be concluded that a forty percent increase of tan$\delta$ is very significant, despite its relatively low value. The recommendation for more frequent measurement was not good enough. The failure could have been avoided by replacing the bushing or adding an intervention monitoring system.

### 3.1.2. Case 2:

In the spring of 2005, the upper envelope of the 123 kV OIP type bushing on a 40 MVA, 110/10.5 kV transformer, 20 years old, exploded. The shock caused damage to the other bushings and equipment in the switchyard as well as a small fire. The failure occurred during a thunderstorm. Previous diagnostic investigation of the bushing had been undertaken in the years 1996 and 2000, approximately nine and five years previous to the failure, respectively. In that period, $\tan\delta$ increased by almost 50 % (from 0,17 % to 0,25 %), but the values were very low, even for new bushings. The bushing was connected by rope. All 123 kV bushing were replaced in a few days. Visual inspection of the bushing debris showed a longitudinal breakdown in the space between the condenser body and the upper envelope (space between positions 1 and 7 in Figure 1). This is implicated by the hole on the central tube caused by the electric arch during the breakdown, Figure 4. However, because of the great damage of the condenser body, most part of which was burnt, a possible cause of breakdown could also have been the condenser body breakdown, although in this case it is less likely. The lower envelope was not damaged; preventing oil leakage onto the fault site and thus it was not accompanied by a major fire or transformer active part pollution by bushing fragments. An inspection of the bushing head showed cracks that could have occurred prior to the failure and this fact could be considered as an initial sealing system defect.

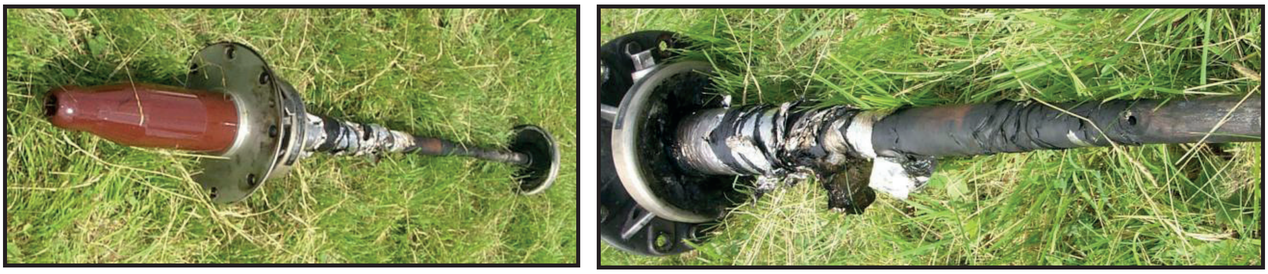


Figure 4: Disassembled failed bushing; Figure left – the whole bushing; Figure right – upper part of the bushing (the hole on the right-hand side of the tube was caused by the electric arch)

The cause of this bushing failure is not completely clear. Possibly, it was caused by a defect in the sealing system or a defect of the bushing condenser body. This case also points out the importance of $\tan\delta$ change during service despite very small actual values.

### 3.1.3. Cases 3, 4, and 5:

In the period of 1991 to 1998, three 123 kV OIP bushing explosions occurred on three GSU transformers 43 MVA, 115 kV in one hydro-power plant. Frequent on and off switching, just as service at full load is characteristic for this power plant (peak load power plant). In all three cases, the failure apearance was practically identical: HV bushing explosion, thus damaging the other HV and LV bushings, causing a fire that further damaged the entire transformer exterior. Each time, repairs lasted for several months and had to be conducted in the factory. The bushings were connected to the switchyard by tubes, as shown in Figure 5. The first failure occurred in 1991 on a transformer produced in 1981. No data on previous diagnostic investigations were available. According to the visual inspection, the burst progressed radially from the central bushing tube (pos. 6 in Fig. 1) to the flange in the test tap area (positions 9 and 11 in Figure 1). The second failure occurred in 1993 on a transformer also produced in 1981. The inspected breakdown traces were visually identical to the first case. Previous diagnostic investigation had been conducted 14 months prior to the failure, but the results did not show any problems. The third failure occurred in 1998 on a transformer produced in 1988. Breakdown traces progressed axially, from the upper endpoint of the bushing, through interspace between bushing condenser body (pos.1, Fig. 1) and porcelain (pos. 7, Fig. 1), to the flange in the test tap area (positions 9 and 11 in Figure 1). Previous measurement of $\tan\delta$, approximately 13 month before the failure, had shown a value of 1,52 %, but, unfortunately, despite this drastic increase in value, the bushing had not been replaced. The three exploded bushings were not produced by the same manufacturer. Traces of all the three breakdowns were in a way associated with the test tap.

Figure 5: Tubular connections between the switchyard and 123 kV bushings

Obviously, these three cases show that something causes bushing properties degradation. The assumption has been made that it is caused by the too rigid tubular connection between the bushing and the switchyard. In addition, the incorrect orientation of the bus dilatation compensator contributes to the degradation (see Fig. 5). It can compensate vertical but not horizontal dilatation, whereas the latter should be dominant. A replacement of the bushing – switchyard connection was recommended. Instead, a part of a tubular connection flexible cable (rope) was used. Switchyard reconstruction was performed approximately twelve years ago and since then there have not been any malfunctions of this type.

## 3.2. 245 kV Bushing Failures

### 3.2.1. Case 6:

Thermal image scanning of the 250 MVA, 220 kV, 16 years old, GSU transformer in 2002 showed increased heating of the 245 kV bushing head and connection (positions 3 and 4, Figure 1) relative to a healthy bushing, approximately by 60 K. Measurement of the HV Winding resistance showed an increase of 0,87 % in the respective phase therefore indicating the cause of poor contact on the tulip contacts (pos. 3, Figure 1) between the connection and the bolt at the end of the copper cable, Figure 6. Inspection of the HV connection showed traces of metal melting on the tulip contacts and copper transfer from the bolt to the aluminum connection. This incipient failure was eliminated by replacing the tulip contacts spring part, since its weakening is the most probable cause of increased heating, and by cleaning contact surfaces. Owing to the availability of spare parts as well as to detection of the malfunction in the initial stage, repairs took only two days.

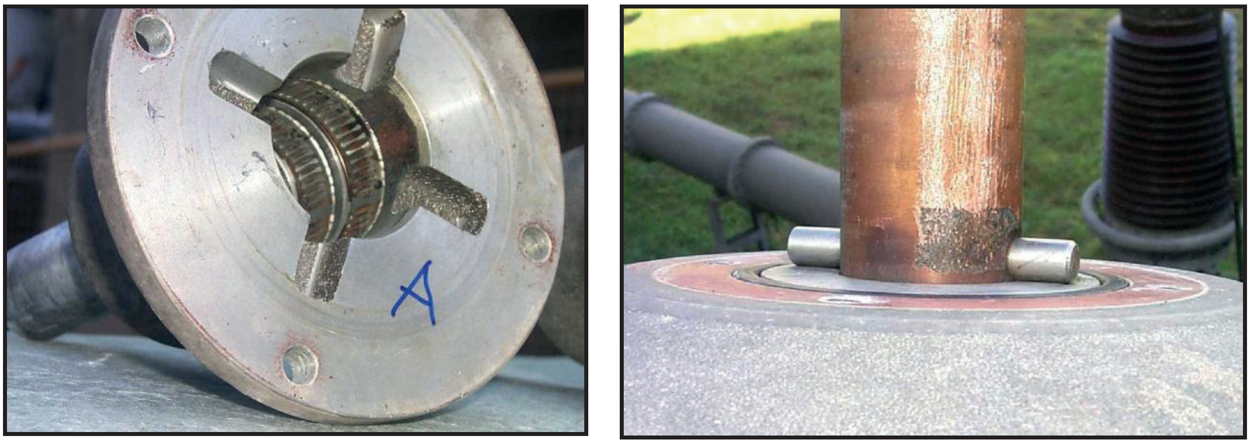


Figure 6: Left: Overheating traces on the HV connection and the tulip contact spring part;
Right: Traces of overheating on the bolt

### 3.2.2. Case 7:

A very interesting 245 kV RBP bushing failure in the form of upper envelope and lower bushing part explosion occurred in 2005 on a 400 MVA, 400/220/30 kV, approximately 25 years old transformer. It was accompanied by a small scale fire on the transformer and pollution of the active part by the bushing fragments and other carbonized residues. Upper envelope fragments destroyed the neutral point bushing and one 420 kV bushing sustained damage, Figure 7. No information on diagnostic tests in the period of 5 years prior to the failure was available. Visual inspection of the bushing indicated a radial condenser body breakdown. Based on a detailed inspection of the bushing, the following probable failure scenario was established. Poor contact on the screw of the upper connection and the connector body (pos. 3, Figure 1) caused overheating which, enhanced during service, resulted in melting of the brazing by which copper cables were fixed to the connector body (Figure 7, 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. Electricity flowed from the tube onto the copper cables through several undefined locations, this being the only possible way to close the electric circle between the switchyard and the winding. Losses on undefined contacts heated the central tube (Figure 7, right) and bushing insulation, leading to condenser body thermal breakdown as a final consequence. Observed overheating traces suggested that the process took a relatively long time to develop and it is not clear why overheating was not detected by the thermal image scanning (generally performed once a year), which could have resulted in prevention of the bushing terminal failure, as it had been done in the previous case. Both failures were physically identical, but in the former case overheating was detected by thermal image scanning and fixed on time, with minimal costs and minimum down-time.

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

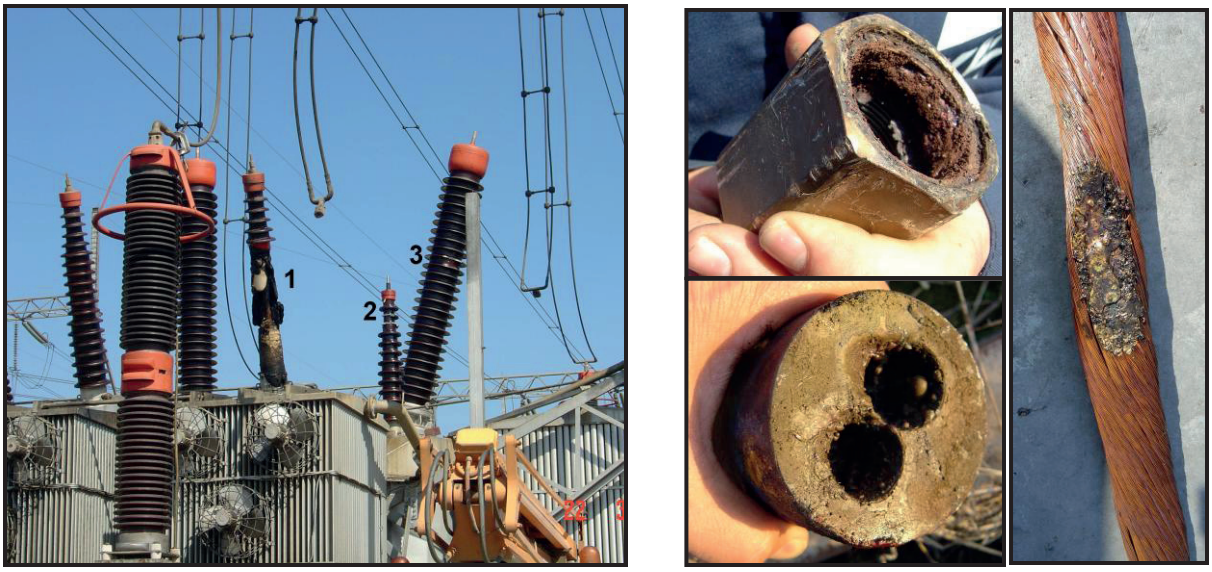


Figure 7: A 400 MVA, 400 kV transformer failure;
Figure left: 1 - burst 245 kV bushing, 2 - destroyed 170 kV neutral point bushing, 3 – damaged 420 kV bushing;
Figure middle top: traces of overheating on the top connection;
Figure middle bottom: connecting bolt body torn off cables;
Figure right: melting trace of brass central bushing tube on the copper rope

### 3.2.3. Case 8:

A failure of a 150 MVA autotransformer, approximately 30 years old, occurred in the spring of 2003. No special indications pointing to the failure mode were visible on the outside. Inspection of the disassembled RBP type bushing showed a burst of the bushing condenser body lower part (pos. 1 in Fig.1), approximately 0,5 m long, Figure 8. The transformer and, especially, the area around the 220 kV winding lead was intensely polluted by the bushing fragments, carbonized insulation and electrodes. Diagnostic tests of the bushing had been undertaken almost eighteen years prior to the failure but there had been no indication of the problem. The connection to the switchyard was flexible, by rope. The cause of this breakdown is not known. However, breakdown traces indicate thermal breakdown with a wear out being a possible cause. According to the author's information, the transformer was scraped.

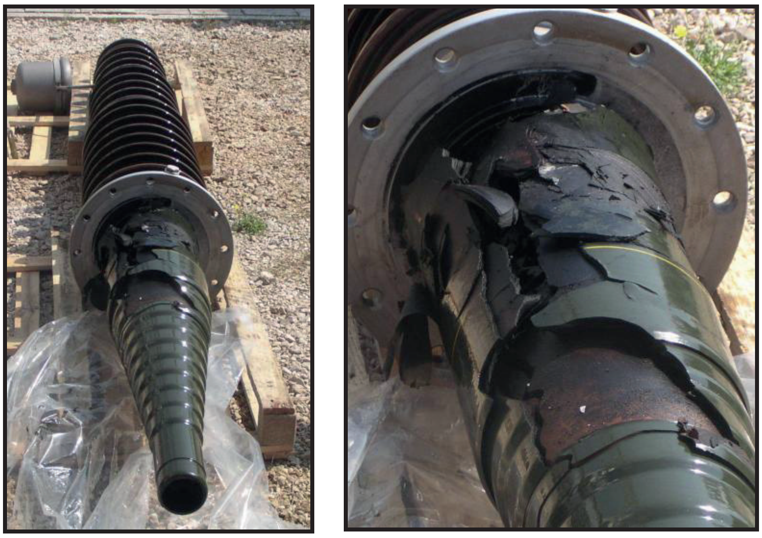


Figure 8 Burst of a 245 kV, RBP type, bushing, the upper porcelain envelope remained intact (left), detail of the burst lower part (right)

## 3.3. 420 kV Bushing Failures

### 3.3.1. Cases 9 and 10:

Two 400 kV bushing failures occurred on a 300 MVA, 400/110 kV autotransformer, one in 1994, the other in 2003, therefore after approximately 8 and 17 years of service, respectively. The bushings were of OIP type, connected to the switchyard by tubular connections, Figure 9. The first failure was of the incipient type – diagnostic tests showed a $\tan\delta$ of 2,2 % indicating a high degree of service unreliability. Visual inspection and DGA of oil confirmed the findings. Traces of carbonized oil and considerable concentration of gases resulting from the electric arch (or wery strong PD) were detected. Previous diagnostic tests had been performed in 1989, when similar $\tan\delta$ of approximately 0,22 % had been found on all three bushings. The bushing was replaced with a spare one with down-time lasting a few days.

The second failure was terminal – an explosion followed by a fire, Figure 9, that could not be put out by the fire protection equipment (water spray system) because bushings are, because of large size, outside its action perimeter. Bushing fragments considerably polluted the transformer, but mostly remained inside the bushing turret. The dynamic shock damaged the 400 kV winding lead. The damages were, with a certain risk, fixed on site, with down-time lasting a few weeks. Traces of breakdown on the bushing condenser body indicated radial breakdown, most probably on the flange level. Diagnostic investigation had been conducted approximately three years prior to the burst, but did not indicate any defects ($\tan\delta$ was 0,23 %).

Figure 9: Bushing terminal failure in 2003 and traces of fire on the 300 MVA, 400 kV autotransformer; The right-hand bushing in the figure was replaced after an incipient failure in 1994. Detail shows the bushing debris and the tubular connection dilatation compensator

It can be presumed that the cause of accelerated bushing degradation could be the tubular connection, even with the applied dilatation compensator (in this case correctly oriented). Service experiences point to the possibility that the compensator can become blocked (seized) after long-term exposure to atmospheric influences, temperature variations etc, after years of service.

### 3.3.2. Case 11:

In 1990 a 420 kV, OIP type bushing exploded on a 725 MVA, approximately five years old GSU transformer. The failure occurred at 658 MVA and caused a fire that had to be put out by the fire brigade. Fire protection equipment (water spray system) had been activated but could not put out the fire because it was located above its action radius. The 420 kV line was pulled out of the coil and bushing fragments considerably polluted the transformer. On the bushing condenser body (pos.1, Fig.1), on flange level, a hole, approximately 4 cm in diameter, with burnt edges can be seen, reaching in depth all the way to the central aluminum tube (pos. 6, Fig.1). Significant electric arch traces can be seen near the test tap. Measurement of the HV bushing capacitance and tan$\delta$ was undertaken in 1989, and the results were satisfactory and similar for all three bushings. The HV connection to the switchyard was double Al/steel rope. Repairs were made in the factory and down-time lasted approximately 7 months.

### 3.3.3. Cases 12 and 13:

On the 350 MVA, 400/110 kV autotransformer, two almost identical incipient failures of the RIP type bushing occurred approximately one after another, the second one after three years service. The monitoring system registered a change of approximately 3 % in the 420 kV bushing capacitance, indicating a breakdown between neighboring condenser electrodes. It was confirmed by measurements on the site and on the dismantled bushing in a high-voltage laboratory. The tan$\delta$ measured before and after the increase of capacitance, practically had not changed. The bushing was replaced with the down-time lasting several days. After dismantling, the bushings were examined in order to locate the breakdown. Results showed that it had occurred between the last condenser electrode (connected to the test tap) and adjacent electrode to it (breakdown across $C_{1n}$ on Fig. 2), Figure 10. The exact puncture location was finally determined by microscope. Visually, the breakdown trace was a hole, around half a millimeter in diameter, stretching from the last electrode to the one before last, designated by the arrow.

In these two cases, the monitoring system proved reliable for fast detection of bushing capacitance changes. The observed traces matched with the measured capacitance values.

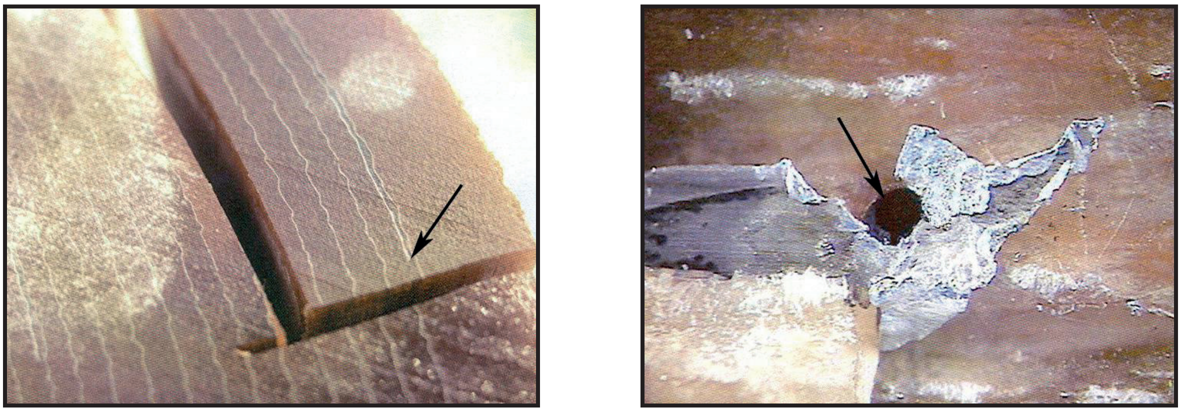


Figure 10: Breakdown position site; Figure left - the puncture is in the material at the depth about 1 cm from the point marked by the arrow; Figure right – the arrow designates the puncture between two electrodes (photo under microscope at magnification x15)

## 4. CONCLUSION

All transformer bushing failures start with a defect that represens incipient failure of the bushing and end with terminal failure – explosion. Such a course of events can be changed by condition diagnostics. In this way, a defect can be reliably detected in the initial stage, considered the incipient failure, before it develops into terminal failure. Based on considerably lower direct and indirect costs of incipient bushing failure as compared to terminal failure, periodic and continuous condition diagnostics has great economic significance.

Bushing failure analysis shows that condition diagnostics efficiency can be enhanced in several ways:

The first improvement presents regular and planned periodical condition diagnostics.

The second improvement presents periodical condition diagnostics enhancement through the application of relative decision criteria for tan$\delta$. Namely, some bushings show considerable tan$\delta$ changes in the period prior to malfunction at relatively low absolute values, even lower than those defined by standard for new bushings [1]. That means establishing and application of the procedure for tan$\delta$ conversion to reference temperature values. It consists of two parts: knowledge about temperature dependence of tan$\delta$, [6], and measurement of the bushing insulation system temperature, which might be a special problem when performed on site.

The third improvement presents the application of continuous (on-line) diagnostics. This relatively new technology is effective in preventing terminal failure. By monitoring the capacitance, it is possible to detect a condenser body defect at a very early phase, while it is so small that it needs to be detected by microscope during visual inspection. In cases of ambiguous diagnostic results, or when a suspicious bushing cannot be replaced (no spares, long term of delivery), installation of a bushing monitoring system is advisable, which, if necessary, could even be of mobile type.

In addition to diagnostics enhancement, service conditions improvement can considerably reduce bushing failure rate. It has been shown that tubular connections degrade bushing properties in a still unexplained manner [7], probably due to their mechanical rigidity. This effect is also reported in [8], where most of the bushings with an on-site measured increase of tan$\delta$ had rigid tubular connections to the switchyard. It seems that the application of bus dilatation compensators is not satisfactory since they can often become blocked during long-term service. A flexible cable connection is a good solution for the problem.

An interesting aspect in failure analysis is that fire protection equipment (water spray system) is often not able to put out a fire caused by a high voltage bushing explosion because the source of fire, due to the bushing size, is outside the perimeter of its efficient action.

## REFERENCES

[1] IEC 600137-2008, Insulated bushings for alternating voltages above 1000 V

[2] R. Krump, H Frielingsdorf: Dry type bushings for operation under difficult conditions, Transform 2001, Munich 23-26. 04.2001. Convention report, 61-74.

[3] H. Frielingsdorf, J. Frost, N. Koch: Future design for transformer bushings, Transform 1998, Munich 20-22. 04.1998. Convention report, 17-26.

[4] An international survey on failures in large power transformers in service, Electra 88, May 1983, 21-48.

[5] CIGRE WG 12.18: Life Management of Transformers, Guidelines for Life Management techniques for Power Transformers, Final report, Draft for comments, 2001.

[6] Mikulecky, A.: Capacitance and dielectric dissipation factor of transformers bushings, Ph.D thesis, University of Zagreb, FER, Zagreb, 2006, (in Croatian).

[7] P.V. Goosen: Transformer accessories, CIGRE 1996, Paris, Ref. 12-104.

[8] Mikulecky, A.: Diagnostics of transformers condenser type bushings, M.Sc. thesis, University of Zagreb, FER, Zagreb, 2003, (in Croatian).