2023 White Paper

Transformer Bushing Failure Investigation

High-Voltage Oil-Impregnated Paper Bushing Reliability, Operational, and Safety Concerns

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EXECUTIVE SUMMARY

In recent years, the nuclear industry has experienced several high-voltage (HV) transformer bushing failures that have raised significant operational, reliability, environmental, and personnel safety concerns. HV bushing is a device used to safely pass an electrical conductor through a conducting barrier such as a transformer tank or circuit breaker case without making any electrical connection to the case.

The bushing failures discussed in this white paper are 230- and 345-kV oil-impregnated paper (OIP) type bushings. This review of four root cause investigations was performed on failed OIP HV bushings to gain insight to limit the reoccurrence of bushing failures. The investigations included bushing teardowns, internal inspections, testing, and data analyses of the failures. Suggestions based on these investigations were used to provide recommendations to improve selection of and preventive maintenance for bushings. This bushing failure investigation was collaboratively supported by EPRI subject matter experts, EPRI members, and industry experts.

INTRODUCTION

Bushings are critical to transformer operation by facilitating electrical power to flow from a power source through a transformer winding and then to connect to the grid or distribution network and finally to the end user. The effects of bushing failures can significantly impact the equipment owner in terms of loss of revenue, outage time, and cost of repairs and can lead to power outages. Bushing failures represent roughly 18% of transformer failures (see Figure 1) [1].

The typical bushing technologies currently available are oil-impregnated paper (OIP), resin-bonded paper (RBP), resin-impregnated paper (RIP) or epoxy (ERIP), resin-impregnated fiberglass (RIF), and newest technology resin-impregnated synthetic (RIS). OIP bushings are the most widely used for power transformers.

In recent years, the nuclear industry has experienced bushing failures that raised concerns with the design and rating practices associated with transformer bushings. Some bushing failures ruptured tanks and ignited fires; others exploded and scattered porcelain across transformer yards. Ruptured transformer tanks can expel oil, causing environmental concerns. These failures resulted in unplanned extended outages that affected plant operation, caused loss of revenue, damaged equipment, and created substantial repair and/or replacement costs. Several industry documents point to bushing failures as one of the main causes of transformer outages.

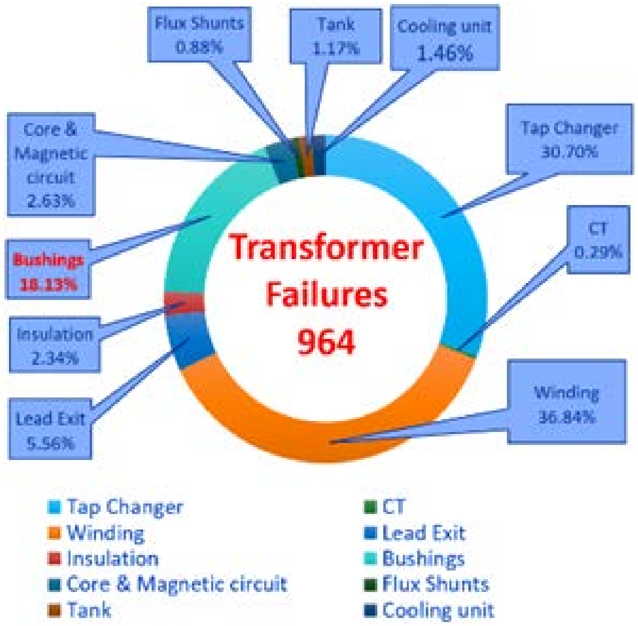

Figure 1. Power Transformer Failure. Source: CIGRE SAC2.37 Report Technical Brochure 642, Transformer Reliability Survey.

According to IEEE, CIGRE, and IEC reports, bushing failures contribute ~17–20% of overall transformer failures globally [2]. In fact, 30% of generator step-up transformer (GSU) failures have been caused by a bushing malfunction [3].

Forensic analysis was performed on three failed bushings to understand the underlying cause or contributing factors to these bushing failures. In some instances, it was observed that the severity with which these bushings failed resulted in transformer failure.

The objective of this paper is to understand some of the key findings from previous root causes. To limit bushing failures, it is recommended to perform routine visual inspections and offline testing as part of the bushing maintenance practices. For critical transformers, continuous online monitoring should be considered.

BACKGROUND

This paper focuses on four HV bushing failures that caused significant operational impact among utility members in the last three years. Three of the bushings' failures in our study were from the same original equipment manufacturer (OEM) with the same make and model of the bushing. The fourth bushing was similar in design to the other bushings but manufactured by a different OEM. However, this bushing failure was different from the other three because it experienced oil contamination, copper migration, and electrical treeing. These challenges led to catastrophic bushing failure after a few years of service.

The general OIP bushing materials of construction consist of insulations (external sheds), kraft paper, insulating oil, seals, gaskets, and other mechanical subcomponents internal to the bushing as shown in Figure 2. The mounting flange is provided with a test tap to measure and test the bushing capacitance and power factor.

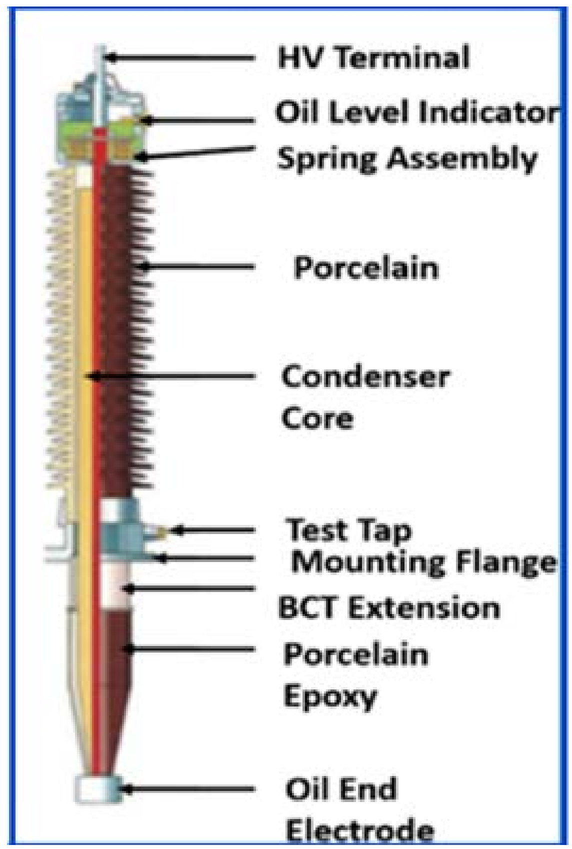

Figure 2. Illustration of OIP Bushing Internal and External Construction

The innermost condenser layer is electrically connected to the mounting flange through a test tap (see Figure 3). For OIP bushings, the condenser body is dried under heat during manufacturing, vacuumed, and then impregnated with insulating oil. Porcelain insulators on the upper and lower sides of the bushing, oil-resistance rubber gaskets, and O-rings are held together with the central tube using a set of powerful springs.

The outermost aluminum foil electrode is grounded through a lead, insulated from the mounting flange of the bushing.

This lead is accessible from the outside and is taken out of the condenser through a device called the *test tap* (also called *measuring* or *tan delta tap*) of the bushing. While in service, this lead is grounded to the bushing mounting flange, usually through the cap of the test tap. This tap can be used to measure the dissipation factor (tan delta)/power factor and capacitance of the condenser bushing offline. With an energized bushing, this test tap is used to measure partial discharge (PD) in the bushing or inside the transformer as illustrated in Figure 3.

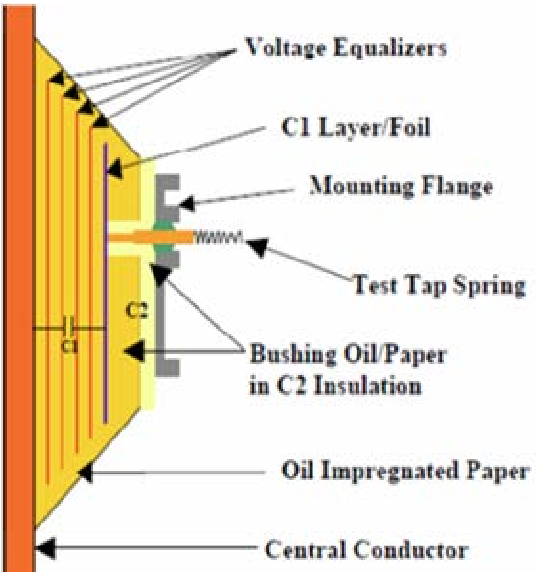

Figure 3. Bushing Internal Configuration: Illustration of Center Conductor, Insulation Paper (C1 and C2) and Test Tap

Figure 4 displays the condenser body consisting of full-width insulating paper and conductive ink layers, forming the capacitive grading layers necessary to control and shape the electric field. To get uniform radial voltage stress and reduce the overall paper insulation thickness, conducting aluminum layers are inserted after every 1- to 2-mm paper thickness so that several capacitors of equal capacitances are formed in series.

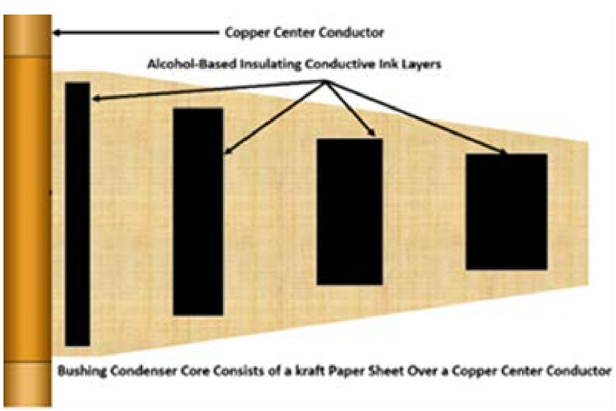

Figure 4. OIP Bushing Graded Kraft Insulation Paper and Conductor Ink Layers

Transformer insulating (mineral) oil fills the space between the shell and the condenser assembly. The oil level and expansion spaces are designed so that the oil level is visible with the bushing installed. The upper (air end) insulator is high-quality porcelain with a shed configuration designed to repel water and limit leakage current.

The inspection included an examination of the failed bushings at the burn-through marks where the failure likely initiated. These observations are considered good indicators of localized internal insulation breakdown. In addition, installation practices, grounding points, and operational and maintenance records were reviewed as part of the overall study.

Bushing materials are subject to electrical stress and degradation over time because of thermal aging, severe weather, and environmental conditions. Poor workmanship and/or manufacturing defects can contribute to degradation. The design also plays a role in bushing performance.

Bushing insulation degradation could be caused by moisture intrusion because of leaks, PD, tracking, and aging. Degradation can also occur from external physical damage, flashover, tracking, and corona. The following are some of the common failure scenarios and the contributors to bushing failure from both manufacturers and/or end users:

- Poor quality of material
- Faulty design
- Bad workmanship, including:
  - Sharp edges of the conductor
  - Incomplete drying of internal paper
  - Bad insulation covering on the conductor
  - Improper joints or connection
  - Improper transportation/handling

These manufacturing deficiencies could lead to the following field degradation conditions that could contribute to more bushing failures:

- Cracking
  - Ingress of moisture: increases the losses and causes the capacitor to become conductive
  - Ingress of solid contaminants: increases the losses and causes the capacitor to become conductive
- Leaking bushings
  - Oil leak (OIP type bushings): leads to electrical discharge/loss of dielectric strength
  - Moisture ingress in the oil and paper

- Direct short to the transformer (phase to ground) catastrophic failure
  - Electrical short circuit between layers: increases capacitance and creates a conductive channel
- Loss of dielectric properties over time (aging)
- Reduction in tracking resistance over time
- Manufacturing defect
  - Presence of voids, cracks, and delamination between layers: causes PDs and insulation erosion, ultimately creating a conductive channel and short circuits of the layers
- Surface cracks on the porcelain
- Change in environmental conditions
  - Lightning strikes
  - Ice buildup or freezing rain
  - Earthquake
  - Wildlife contact

Bushing Design and Manufacturing

The OIP bushing has been the bushing of choice for utilities for over a decade. When OIP bushings were introduced to the market many years ago, they provided several reliability improvements over other bushing designs commonly available at the time. The 230- and 345-kV OIP bushings are widely used in the United States and internationally.

These bushings were designed to meet the requirements of the applicable electrical and dimensional standards. Although OIP bushings have proven to be popular, they are still one of the causes of transformer failures. The actual failure numbers are low in comparison to their population; however, the consequences of their failure are high and therefore unacceptable for nuclear power plants.

The failure of this bushing type has caused collateral damage when the porcelain sheds shatter. Figures 5 illustrates the severity of a failure. In some cases, the associated transformer was damaged or destroyed.

Figure 5. Illustration of Destroyed OIP Bushing Sheds

The violent nature of these bushing failures has resulted in many utilities investigating alternative bushing designs such as RIP, RIS, or RTF bushings. The OIP bushings have been the industry preference, and replacing them represents a significant capital investment because of this bushing type's large population and replacement cost.

Methodology: Bushing Failure Investigation

It is important to follow a consistent process or methodology when performing a failure investigation to limit contamination and to avoid destroying important evidence that could aid with an overall root cause discovery. The investigation process consists of four phases: fact-finding and preliminary analysis, destructive dismantling, laboratory investigation through tear-down, and finally the root cause analysis. Failure investigation teams should have knowledge and experience in performing forensic analysis and failure scenarios.

In support of this investigation, several industry bushing failure/root cause analysis reports, standards, and publications were reviewed. In addition, actual bushing tear-down investigations were performed at the EPRI laboratory in Lenox, Massachusetts to better understand the overall failure cause of these bushings.

Transformer Bushing Failure Study Case #1

The first case study covers a recent bushing failure at a member's nuclear generating station. Figure 6 shows the damaged GSU. This HV bushing failure led to a catastrophic transformer failure and a costly forced outage.

Figure 6. GSU Transformer External View: Catastrophic Failure of HV Bushing Center Phase

As part of the failure investigation, the transformer maintenance history including the dissolved gas analysis (DGA), oil quality, historical bushing power factor (PF), and capacitance test data was reviewed; no issues were noted from this review.

The heavily damaged H2 bushing was removed from the transformer and brought to EPRI's Lenox lab for teardown and detailed examination. The subject bushing was a porcelain 230-kV oil-impregnated bushing manufactured in 2009. The condenser core consists of kraft paper sheets wrapped over a copper center conductor and electrically graded using conductive ink layers as shown in Figure 4. The condenser core was heavily damaged by fire, with most of the fire damage at the lower and upper ends of the condenser core. Prominent arc flash damage with significant melting of the copper center conductor was located near the lower end of the center conductor as shown in Figure 7.

Figure 7. B-Phase Extended Internal Damage of 230-kV Bushing with Copper Center Conductor

No other evidence of arcing was noted along the center conductor as shown in Figures 7 and 8. Examination of the H2 bushing capacitance stud and the cover displayed

no pitting or other evidence of significant fault current flow. This suggested that there was not an electrical failure in the middle axial region beneath the axial extent of the capacitance tap. It also suggests that the capacitance tap foil layer was not within the conduction path of any electrical failure progression.

Some ink layers had small gaps where the ink was not wholly applied. There was no evidence of PD activity in these areas; however, there were several paper strips wound into the paper layers at two locations toward the bottom of the condenser core and aligned axially with the location of the prominent main arc point as shown in Figure 9.

The working hypothesis is that the paper layers found at the two locations of the condenser core are sliced off from the lower end to form the lower taper that was inadvertently wound in during the lower end winding process. Given the location of these strips in the direct vicinity of the main failure point, the presence of these errant paper strips may have played a role in the failure. In the layers of paper nearest the center conductor, a second area of torn paper and carbon was noted above apparent arc strike marks or deformation almost the size of a golf ball in the copper of the center conductor near the main arc point (roughly 2 in. [51 mm] away circumferentially) as shown in Figure 8.

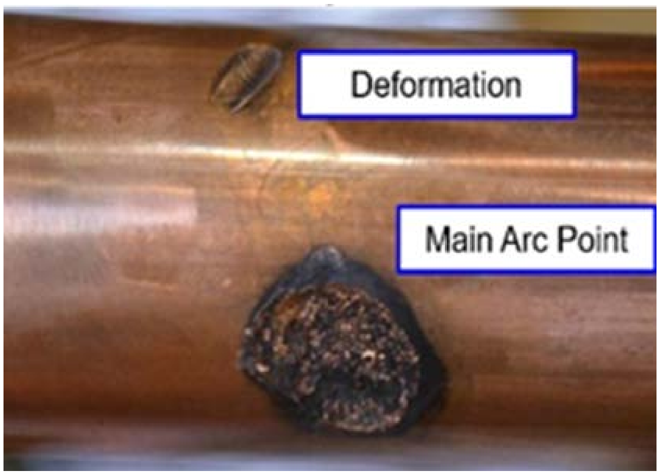

Figure 8. B-Main Arc Point of 230 kV with Copper Center Conductor

Examination of the bare center conductor shows mechanical deformation in this area, a raised edge of approximately 1/8 in. (3.2 mm). There does not appear to be melting of the copper in this area that would be indicative of arcing. The upper and lower ends of the center conductor were also examined for any evidence of overheating. Any discoloration observed was consistent with the fire that followed the failure and not long-term overheating.

The key findings from the forensic examination of the H2 bushing remnants are depicted schematically in Figure 9. This figure illustrates the main arc points on the center conductor and shows the approximate path of the electrical failure to the ground sleeve. Note that the path of the arc extends outward from the center conductor and then up through the oil gap between the lower taper of the condenser core and the lower porcelain, up to the lower capacitor edge of the ground sleeve bypassing the grounded capacitance tap layer.

In discussing potential failure causes, the initial conversation included the possibility of a failure external to the bushing (perhaps in the active part) such as the transformer main tank or environmental external conditions. The known arc termination points inside the bushing reveal a dielectric failure toward the lower end of the insulated condenser core. The only termination along the center conductor was located 400 mm (15.74 in.) from the lower end of the center conductor and beneath 13–15 conductive layers of the insulation or roughly 1/3 of the total radial build of the solid insulation shown in Figure 9.

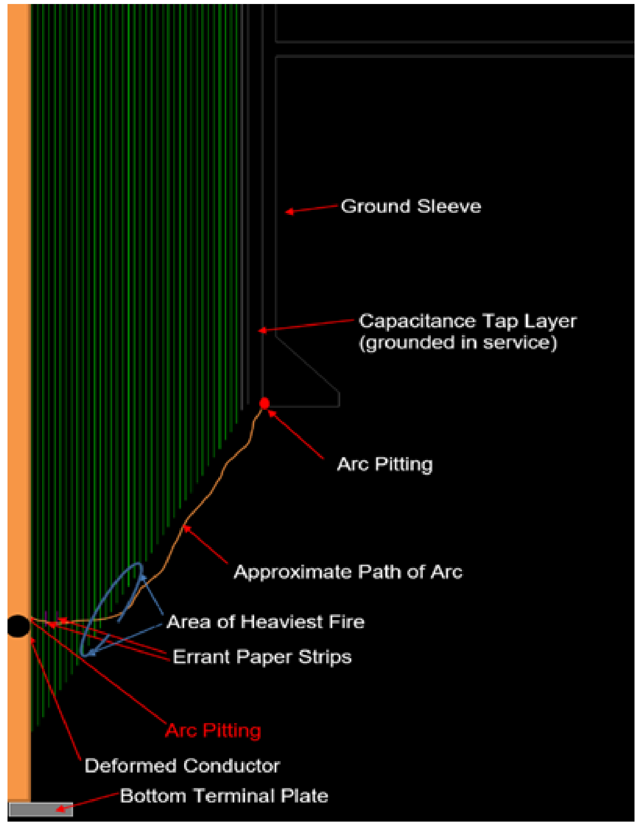

Figure 9. Illustration of Diagram of Lower End of H2 Bushing Depicting Key Findings from Forensic Examination

If this failure was a result of the bushing coming apart because of a postulated pressure wave from a failure in the main tank, the arc terminations would likely be located on uninsulated portions of the center conductor or the lower bushing terminal ground sleeve rather than beneath many layers of paper insulation. Therefore, it is most likely that an electrical failure occurred within the bushing itself, either as an initiating event or concomitant with a failure within the main transformer tank.

There are two possibilities that could dielectrically fail the bushing: 1) either the strength of the insulation is compromised by some contamination or defect or 2) the electrical stress exceeds the bushing design rating of the insulation. Each of these possibilities was examined more closely.

There was no evidence of excessive transient or operating voltage levels at the time of failure caused by lightning or switching operations in the vicinity. In addition, there was no information that would suggest that the transformer experienced operating voltages exceeding the expected bushing design rating. The possibility of transformer winding failure and the resultant excessive voltages on the bushings were also evaluated, but the fault recorder data suggested that the fault was near the HV terminal of the transformer.

Therefore, based on the evaluation, it is unlikely that either system conditions or an initiating failure external to the bushing would have been the result of excessive voltage to ground at the time of the bushing failure. Absent excessive voltage to ground, the bushing may still have experienced enhanced electrical stress at the lower end of the bushing. If the lower end of the bushing was not properly shielded or there were insufficient electrical clearances to ground (tank wall), it is theoretically possible that the electrical stresses along the lower taper of the condenser core as shown in Figure 9 could have increased beyond the rating of the bushing. However, such conditions would have to be present from the time of manufacture. Through observation and interviews of plant personnel who performed this bushing installation, it was confirmed that there was no change in the lower end shielding before or after it was installed.

It is most likely that some conditions existed within the bushing that reduced the strength of the insulation in the lower end of the bushing. Note that much of the insulation in and around the area of the prominent arc flash point was destroyed in the subsequent fire. This makes a precise and certain understanding of the progression of the electrical failure difficult. Specifically, direct evidence of any defect, void, or other initiating cause of the electrical failure was destroyed in the arc flash caused by the failure that followed.

It is possible that this deformation of the center copper conductor resulted in sufficient PD to form a void of decomposition gases in the main arcing point (given the relative proximity). There is also the possibility of a similar deformation around the main failure that is no longer evident because of the melting of the copper in that area from the main power arc.

It is conceivable that the same mishandling that resulted in the known copper deformation on the conductor caused another area of mechanical damage that then resulted in an area of persistent PD that then progressed to failure. As a final note, the GSU fault was not immediately suppressed but remained energized because of the capacitive nature of the generator, which continued to emit current during the coast-down from running speed to zero. The fault evolved from a phase-ground fault to a phase-phase-ground fault. Undoubtedly, there was additional arcing after the bushing porcelain ruptured, resulting in arc strikes external to the bushing.

Figure 10. Discovery of Errant Paper Strip Between Ink Layers

During bushing disassembly, an errant paper strip, as shown in Figure 10, was found wound on the condenser core, which could create a small void at the edge of the strip where it rests between the adjacent layers of paper insulation. This void may have been larger in areas where the strip is wrinkled or folded back on itself. Because the permittivity in the void is lower than in oil-impregnated paper, the electrical stress would be higher in the void. This condition could result in PD activity in the void. PDs generate gases and could carbonize the adjacent paper insulation, forming conductive byproducts and perpetuating the discharge. This cycle of degradation would progress until sufficient solid insulation was damaged to compromise the dielectric strength of the insulation, resulting in dielectric failure.

As shown in Figure 11, a mechanical "deformation" was noted on the surface of the center conductor near the main failure point. Some carbon and torn paper were noted, extending several paper layers out from the surface of the center conductor. The "deformation" has a raised edge of about 1/8 in. (3.2 mm). This protruded edge would cause increased stress because of the divergent electrical field caused by irregularities in the conductor surface. In addition, the paper insulation would not sit flat over this area, creating an air gap that would provide an initiation site for partial discharging to occur. Although some or all of the carbon may be from the main failure, it is likely that there was some PD activity in this area.

Figure 11. Illustration of the Main Arc Point and Deformed Center Conductor

To summarize, the following hypotheses explain what was observed. The initial failure was most likely internal to the H2 bushing, flashing from the center conductor approximately 15.74 in. (400 mm) from the lower end, arcing outward through the layers of paper insulation and conductive ink, then traveling through the oil gap between the condenser core and lower porcelain up to the ground sleeve.

Two possible defects were noted that support the hypothesized failure cause:

- Two paper strips that appear to be remnants from slitting the paper for the lower taper were found wound at the same axial location as the main arc point.
- A significant deformation was noted in the vicinity of the main source of fire fault puncture, with an approximately 1/8-in. (3.2-mm) raised edge. Given the evidence of PD activity from much smaller pitting observed on the H1 and H3 bushings, this deformation of the conductor would likely have resulted in damaging PD activity.

There may also have been a deformation of the conductor in and around the area of the main arcing point that was obscured by the subsequent melting of the copper in that area.

It is likely that there was a significant change in the electrical environment of the lower end of the bushing that contributed to the failure; however, there is no evidence that would suggest a significant change. There was no conclusive evidence of overheating of the H2 bushing. Any discoloration of the lower and upper ends of the center conductor was consistent with, and therefore likely the result of, the fire that followed the failure. No discoloration was noted on the H1 and H3 bushings.

EPRI has received no evidence that would suggest that an outside event initiated the failure of the H2 bushing. The investigation shows evidence that the bushing failure may have been initiated from inside the H2 bushing.

Transformer Bushing Failure Study Case #2

In this case study, the transformer bushing failure led to a reactor trip and fire on the GSU transformer. The fire ignited the B-phase high-voltage bushing as illustrated in Figure 12. During the initial inspection of the B-phase HV bushing, arc strike damage was discovered on the bushings, grading rings, and surrounding structures.

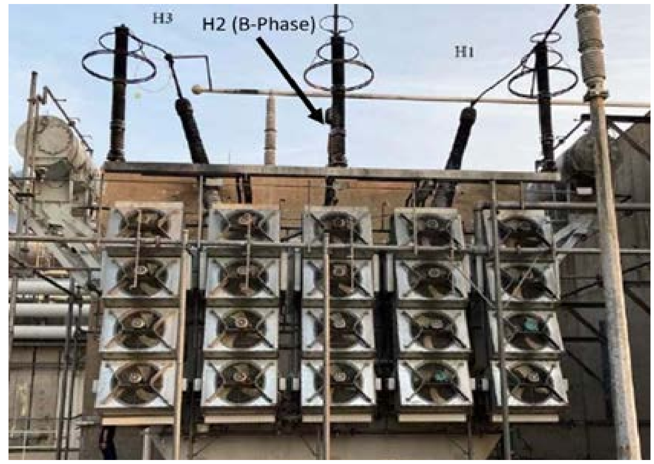

Figure 12. Image of H2 Bushing Catastrophic Failure

The bushing in Case #2 had metal foil for the voltage tap connection. Along with the adjacent insulation paper burn marks, creases were discovered during the unwinding of remanent paper layers in the H2 bushing similar to the Case #1 assessment. This is most likely the initiating point that led to the failure condition.

A low energy fault at this point contaminated the insulating oil, and the contaminants were dispersed throughout the bushing. Kraft paper located near the voltage tap connection appears to have been degraded during the low-energy fault and affected the power to follow the path (the current that flows after the conduction path is established) during the catastrophic failure.

Moreover, during generator spin-down, Figure 13 shows that a major fault occurred 64 in. (1.63 m) below the top of the H2 bushing, which was halfway between the top of the bushing and the top of the mounting flange. Arc strike marks on the voltage tap pin and the internal adapter were also noticed in the H2 bushing. Multiple arc strike marks were also discovered on the H1 and H3 bushing expansion chambers, grading rings, and surrounding structures.

Figure 13. Illustration of 345-kV Bushing: Close-Up of the Major Fault Location Through the Insulation to the Center Conductor

Although H1 and H3 were not destroyed, during the bushing teardown all three bushings had metal foil creases inside the insulating papers. The voltage tap had pin scratches on the bushings that may have been a source of electrical stress. At 345 kV, all creases and scratches can be a stress point that could result in catastrophic bushing failure as shown in Figure 14.

Figure 14. Illustration of A-Phase HV Bushing and Mounting in a Turret with a Surge Arrestor

Metal foil for the voltage tap connection along with the adjacent insulation paper burn marks and creases were discovered during the unwinding of remanent paper layers in the H2 bushing. As a result of this assessment, the team concluded that this is most likely the initiating point that resulted in the catastrophic bushing failure.

Bushing Failure Investigation Case #3

In 2022, another nuclear power plant experienced a catastrophic GSU failure because of a 345-kV bushing failure. The station assigned an investigation team to determine the root cause of the bushing failure. The results of its investigation identified that the failure originated in the HV bushing, causing irreparable damage to the GSU and nearby equipment. The 345-kV switchyard breakers operated and isolated the electric transmission system, which was supplying the current to the fault. This resulted in an automatic turbine-generator trip and unit scram. The station switchyard fault recorder waveforms were analyzed and showed that during the transformer bushing fault, the A-phase-to-ground fault current illustrated that the line-to-ground fault on the wye side looks like a phase-to-phase fault on the delta side.

The station root cause team along with the bushing manufacturer performed a teardown of the failed HV bushing at the factory. The failure investigation team revealed that the condenser of the bushing had suffered significant damage. Because of the catastrophic nature of the event, the porcelain shell was shattered and little remained.

During the initial investigation, the team discovered that the condenser bushing had shifted a few inches away from its lower support and observed a burn hole approximately 1 in. (254 mm) in diameter. During the disassembly of the condenser body, several incomplete or partially printed ink equalizers were discovered. After the investigation team unwound the insulation paper, a hole was revealed that identified where a PD “treeing” had occurred.

Figure 15. Illustration of Ink Printed Layer Treeing

The investigation team believes that the printing defect shown in Figure 15 was the problem. Over many years of energized service, this condition can cause slow and progressive insulation degradation. Figure 15 shows conductive ink lines that have existed since the original fabrication—those lines should not be there. The lines on the insulated paper created stress points within the grading layers of the bushing; the capacitance is no longer equal. This unequal grading of the capacitance over time would degrade the insulation of the condenser to withstand the penetrating electrical field caused by current flowing through the conductor.

Some ink layers had small gaps where the ink was not wholly applied. There was no evidence of PD (breakdown) activity in these areas; however, for a bushing to perform successfully over many years, the insulation must remain effective both in composition and design shape and is the critical factor in the bushing's survival.

Figure 16. Punctured Insulation Because of Leakage Path Overcomes the Dielectric Strength

In general, HV bushings are designed to withstand the high electrical field force or stress produced in the insulation when any grounded conditions occur. As the strength of the electrical field increases (electrical force), leakage paths may develop within the insulation as shown in Figure 16 along the red arrows. If the energy of the leakage path overcomes the dielectric strength of the insulation, it may puncture the insulation and allow the electrical energy to conduct to the nearest grounded material, causing burning and arcing as shown in Figure 17.

Figure 17. Illustration of Punctured Conductor with Signs of Arcing and Burning

The root cause team concluded that the most probable cause of the 345-kV bushing failure was the presence of one or more manufacturing defects related to printing ink. The vendor investigation team believes that the improperly designed ink layers initiated the electrical event, resulting in an electrical discharge. This discharge continued until pressure was generated, which shattered the remaining kraft paper around the condenser—creating an arc with enough energy to cause overpressure and ultimately leading to a catastrophic failure of the HV bushing.

The design deficiency caused high stresses from ink inclusions, and PD developed between bushing condenser layers. The PD created a large amount of trapped gas inside the bushing condenser, resulting in an insulation void containing hydrogen gas that did not have time to migrate out of the condenser. The gas space resulted in a mechanical detonation, blowing apart the lower porcelain and the insulation of the lower condenser. High electric stresses make the bushing less tolerant of any sort of defect.

Bushing Failure Investigation Case #4

In this case, the transformer was equipped with 345-kV bushings. This station automatically scrammed on the GSU transformers phase-to-ground fault and fire. Figure 18 shows the A-phase HV bushing that suffered catastrophic damage.

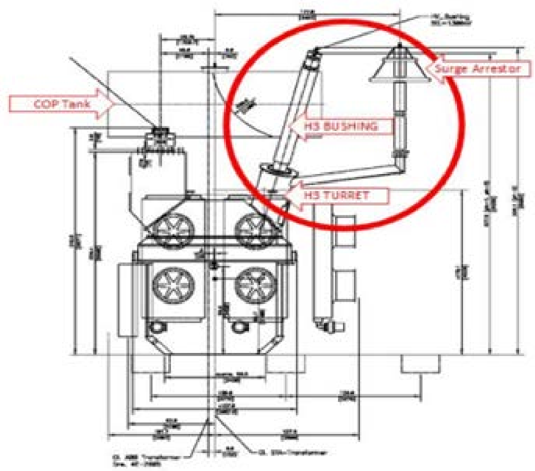

Figure 18. Illustration of A-Phase HV Bushing and Mounting in a Turret with a Surge Arrestor

The root cause analysis team was able to review all the historical trends of the transformer's oil analysis as well as monitoring data—including electrical testing prior to the failure—and did not discover any issues.

The team's evaluation was based on the extensive failure history associated with this style of bushing, the physical characteristics of the catastrophic failure, various root cause analysis reports, and the analysis performed as part of this investigation.

The team concluded that this failure was a sudden, unanticipated, catastrophic HV bushing failure because of an unknown material issue attributable to manufacturing and/or design issues by the original equipment manufacturer (OEM).

Additional Failure Information

Doble Engineering, NRC publications, and the INPO-IRIS database were reviewed for additional bushing failure cases. Furthermore, additional discussions with bushing OEMs, nuclear utility members, and other industry stakeholders were conducted to obtain additional bushing operating experiences.

From these reviews, additional failure mechanisms became apparent relative to these bushing failure cases such as copper migration and electrical treeing issues. These failure mechanisms can impact the bushing insulation paper.

The issue with copper center conductor degradation is well known across the industry [9]. According to the bushing manufacturer's report, copper migration was attributed to the type of oil being used in the bushings, especially bushings manufactured in 1999 and 2001 in the manufacturer's facility. The manufacturer believes that copper is migrating from the copper center conductor and creating copper trees within the paper structure shown in Figures 19 and 20. The mechanism of how the copper migrates from the center conductor has yet to be determined. The following statement was noted by bushing manufacturers at the 2010 Doble Engineering Company 77th Annual International Doble Client Conference [4]:

The fact that copper ions from conductor surfaces are taken into solution in some transformer mineral oils and then deposited onto paper insulation in bushings and transformers has been well documented. These deposits have been implicated in a number of instances of equipment failure. Corrosive sulfur in transformer oil has been suggested as the cause for both the migration and the deposition of copper on the paper insulation in these instances even though the oil has consistently tested as non-corrosive. The migration and deposition of copper in transformer oils have been demonstrated to be independent of corrosive sulfur, or otherwise. The process of taking copper into solution and then depositing the copper as a fixed, stable compound on paper insulation is dependent upon the formation of copper-organic polar compounds in solution in the oil, attraction of these compounds to the surface of Kraft paper, and the formation of stable copper compounds in a pattern that decreases the dielectric strength of the paper insulation [1]. This paper presents one case of a copper migration-induced failure in three separate transformer bushings.

In many instances during this investigation, when the bushing was unwound, electrical treeing was observed in the paper at the high-stress edges of the foil layers. Electrical treeing compromises the axial and radial breakdown strength of the paper layers because these are three-dimensional structures. As the insulation quality breaks down, the electrical withstand strength decreases between adjacent paper layers. At some point, the dielectric breakdown between layers will occur. A breakdown between layers results in an avalanche condition in which full-scale breakdown progresses rapidly and without significant warning. With electrical treeing, the insulation structure of the bushings may not withstand its normal voltage stresses. It is our hypothesis that the presence of electrical treeing could be what led to the rapid and complete breakdown of the insulation system.

In general, PD has been detected in transformer tanks with online acoustic monitoring sensors; however, it has not been shown that treeing in the bushing insulation can be done with online acoustic monitoring. Rather, it has been discovered upon bushing teardown. The bushing that failed was successfully Doble tested 2 years and 6 months prior to failure, with no anomalies noted.

A bushing OEM publication suggests that metal migration and semi-conductive copper sulfide migration in oil led to surface contamination of bushing insulation. Stress from this contamination is considered a causal factor for bushings insulation degradation as shown in Figure 19.

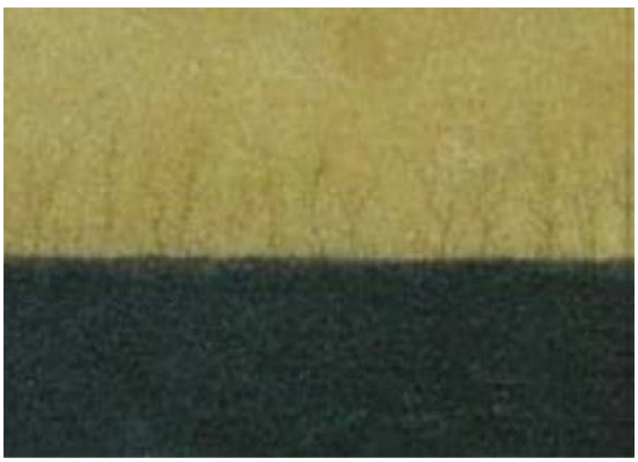

Figure 19. Image of Bushing Failure "Trees Trace" with Signs of Copper Sulfide Migration

The bushing manufacturer believes that copper is migrating from the copper center conductor and creating copper trees within the paper structure. Based on this position, the bushing OEM believes that bushings with aluminum center conductors would not be susceptible to the failure mechanism (electrical treeing). This is an area that requires additional research to better understand metal migration and to determine what metal(s) are susceptible to this degradation.

It appears that electrical treeing was caused by the manufacturing/design of the foil edges. The foil edges were cut with a device similar to a standard office paper cutter. This results in "sharp" edges that do not control the electrical stresses at the foil/paper interface, as shown in Figure 20.

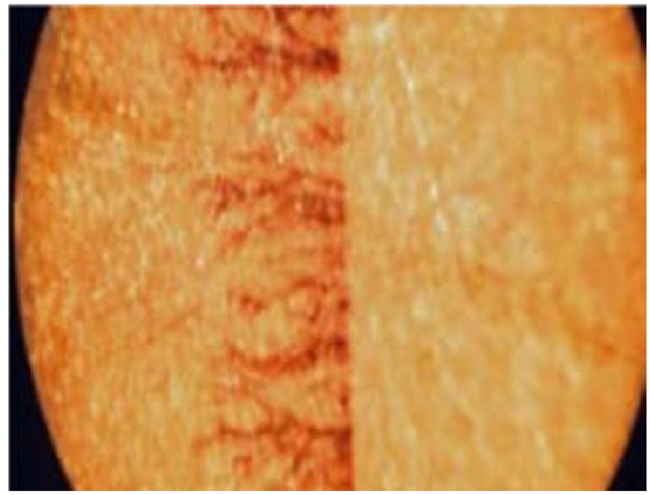

Figure 20. Image of Copper Migration Witnessed on Oil Bushings Equipped with Copper Conductor

As mentioned in the introduction of this paper, there are other challenges in bushing failure; some of the issues include copper migration, gas bubbles in the insulation, and draw lead arcing. Other issues could be Cu2S-wax contamination, failing tap connections, overheating, top terminals, bushing selection, and polar compounds in solution in the oil that could decrease the dielectric strength.

It is believed that electrical stress at these sharp edges can cause electrical treeing on the paper. The analysis of the paper, foil, and oil did not reveal any other anomalies that would have led to the treeing. Other manufacturers use precision cutting techniques to cut the foil and fold over the edges. It appears that these techniques result in smooth, rounded edges that control and minimize electrical stresses.

In Case #4, the failure investigation team's report indicated—and it was also noted during bushing assembly—that the bushing foils were manually placed into position using only a template for alignment (other manufacturers may use devices such as laser alignment). This method could result in misplaced foils, even if by fractions of an inch, which could alter the capacitive grading—potentially further weakening the already degraded insulation system. The foil-cutting and placement process described above is used for the assembly of all bushings at one manufacturing facility.

During the teardown of this bushing, the utility contracted a third-party technical expert and another major bushing manufacturer to support the bushing failure analysis. The technical experts pointed out a potential concern with the foil-cutting process used by the manufacturer of the failed bushing. It was noted that modern manufacturing processes use lasers to cut the foils and then the edges are folded over, preventing an increase in the electrical stress concentration caused by sharp edges.

In another failure investigation, one utility performed a teardown of six of the same type, make, and model of the bushing. One of the bushings had shown the presence of electrical treeing in the paper insulation. If the remaining bushings are left in service, there may be an increased risk of a catastrophic in-service failure.

In this case, the teardown of the failed bushing revealed a puncture hole in the inboard end of the bushing that radiated outward to the bushing's ground flange. When the bushing was unwound, electrical treeing was observed in the paper at the high-stress edges of the foil layers. As stated previously, the breakdown between layers results in an avalanche condition that progresses rapidly and without significant warning, which reduces the bushing withstand capability—even to normal voltage stresses.

The deposition of copper onto paper insulation in bushings and transformers has been well documented. These deposits have been implicated in several instances of equipment failure. Corrosive sulfur in transformer oil has been suggested as the cause for both the migration and the deposition of copper onto paper insulation in these instances even though the oil has consistently been evaluated as non-corrosive. The migration and deposition of copper in transformer oils have been demonstrated to be independent of sulfur, corrosive or otherwise.

This case study discusses migration-induced failure in three separate transformer bushings manufactured by the same manufacturer and filled with a certain type of mineral oil. One utility has used an independent bushing manufacturing vendor to perform a bushing failure investigation. However, the independent vendor did not find evidence to support the copper migration theory.

Bushing Failure Mitigation Strategy and Recommendations

This white paper evaluates recent bushing failures by reviewing utility practices on maintenance, testing, diagnostics, and failure analysis of OIP high-voltage bushings.

A bushing failure can result in equipment damage, risk to personal safety, increased system disturbance, and loss of production or scram.

OIP bushings have been the focus of this paper because of recent failures. A recent survey revealed approximately three-hundred fifty 345-kV bushings at U.S. nuclear power plants. Of this population, there were four catastrophic failures in the last two years. Statistically, this number of failures would be considered low; however, the consequences of these failures have been significant.

From the investigation and developed hypotheses, no single most probable cause of the failures could be identified. However, the review of HV OIP bushing failure investigations appears to reveal the presence of one or more manufacturing defects.

In some instances, the investigation discovered workmanship issues that are thought to have initiated a bushing failure. In some cases, the bushing failures appear to be caused by rapid or sudden bushing deterioration, in which periodic testing would not have detected a degraded bushing prior to failure.

Bushing monitoring equipment is designed to detect continuous changes in power factor, capacitance, and PDs because of particle contamination. More than a dozen bushing monitoring systems are available in today's market that use different analytical techniques to evaluate bushing conditions.

As a result of the bushing failure assessments from the case studies, users should consider the following suggestions to help mitigate some of the vulnerabilities of OIP bushings:

- Because some failures were attributed to bushing design and manufacturing issues, end users should consider a bushing specification and a design review visit and witness factory acceptance testing for replacement bushings at the bushing manufacturer's facility.
- Users should consider discussing the electrical treeing phenomenon during the bushing design review and/or

factory testing of OIP bushings—in particular, the 230- and 345-kV bushings with copper center conductors. Oil type and testing should be discussed to limit the use of oil with corrosive properties (that is, sulfur and other contaminants).

- Research should be conducted to understand conditions that lead to metal migration onto paper insulation. This should include copper and aluminum center conductors.
- Analyzing the data is a critical part of a successful condition-based monitoring program. Trending the data and establishing alarm points are essential for effective communication of equipment conditions. In addition, continuous online monitoring technologies can be used to collect condition data.

To address OIP bushing failures, many users are considering alternative technologies such as resin-impregnated paper and resin-impregnated synthetic bushings. These bushing designs could improve personal safety and other risk factors such as transformer fire and collateral equipment damage that occurs when bushings with porcelain sheds fail.

As noted in Case #4, electrical treeing cannot be detected with any known test methods. Industry operating experience has shown that certain bushings that failed after two or more years of service appear to have been impacted by this failure mechanism. To understand electrical treeing, further focused research is suggested to understand the failure mechanism and how much time is required for this failure to manifest.

Finally, based on these case studies, further research is needed to understand the mechanisms by which paper degradation occurs at the interface with the bushing center conductor. In some of the failure conditions, copper sulfide has been noted to have led to insulation degradation. Although metal migration has been noted to occur with copper conductors, aluminum conductors are used by some manufacturers. Research should be done to determine when metal migration occurs and what materials are susceptible to this issue. Research should be considered on the chemical processes occurring in the insulating oil that contribute to the vulnerability of other components in a transformer. It should be noted that bushing insulation degradation could be observed only during the teardown of these bushings.

REFERENCES

[1] CIGRE TB 755, Transformer Bushing Reliability Survey Feb 2019.

[2] CIGRE Transformer Reliability Survey, TB 642, Section 2.1.5 Bushings, Working Group A2.37, December 2015.

[3] CIGRE Transformer Reliability Survey reference WG A2.37 dated April 2012.

[4] Doble Engineering Company 77th Annual International Doble Client Conference.

[5] *High-Voltage Current Transformers and Bushings: Failure Prediction and Prevention Symposium*. EPRI, Palo Alto, CA: 1999. TR-113649.

[6] *Bushings Guidebook Development: Failure Investigation and Monitoring Effectiveness.* EPRI, Palo Alto, CA: 2019. 3002015695.

[7] IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings. IEEE Standard C57.19.00-2000.

[8] Insulated bushings for alternating voltages above 1000 V. IEC Standard 60137.

[9] https://www.nrc.gov/docs/ML1208/ML12088A511.pdf.

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