



ROLE OF VERY FAST TRANSIENTS IN HV TRANSFORMER BUSHING FAILURES AND ITS REMEDIAL MEASURES

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ABSTRACT

Without HV Bushings, large transformers are unthinkable and failure in any of the bushing results in transformer failure as well. Bushing failures are rarely analyzed separately from the transformer failure. The approach laid out in this paper is to expand bushing failure research so that besides terminal transformer failures, incipient failures (non-transformer-damaging) are also looked up to. Bushing failure mechanism in the presence of very fast transients (VFT) during AIS bus bar switching lead to certain failure scenario, that is been described and supported by a case study. Mitigation measures for such failure mechanism are also suggested.



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I. INTRODUCTION

High Voltage (HV) Bushings are the most frequent cause of failure in transformer failures. According to various researchers, HV bushings cause 5 to 50% of the total no. of transformer failures which leads to fires, huge collateral damage and accidents [1]. Bushings are the transformer's crucial component, and one transformer can have up to 10 bushings. A failure in any one of them leads to transformer failure as a consequence. A single bushing burst can damage the transformer in many ways. Burst can damage the transformer in such a way that conductive and burnt debris could contaminate its active part. Wiping out bushing fragments from transformer's active part is a difficult task with doubtful results. Transformer bushings are normally installed on the hottest part of the transformer tank and are exposed to highest and lowest ambient temperatures [2]. This combined with external mechanical forces results in huge demand for bushing insulation and its sealing systems. The electrical field intensity of bushing's HV condenser body is the highest amongst the power equipment installed in HV substation [3]. To prevent bushing failures, they are subjected to condition monitoring with varying effectiveness in different methods. Transformer bushings, their design, properties and their failure analysis are not often a topic of transformer related literature papers. Further section in the paper provides readers with an insight into an incipient failure (non-transformer-damaging) case study of a bushing failure where root cause analysis was carried out by the authors.

II. DETAILS OF FAILURE INVESTIGATION

The contents of the case study are based on the observations/results of the work carried out by the authors and the inputs/data provided by the electrical utility operating and maintaining the transformer. The cause of failure was investigated in the framework of the input data, photographs, fault recorder data and failed bushing components provided by the electrical utility for root cause analysis of condenser bushing and inference drawn from observations or measurements made in testing and analysis. Various analysis were done including visual observation of the failed component, collection of service related and fault recorder data, study of working conditions and operating parameters, macroscopic examination using stereo microscope, scanning electron microscopy (SEM) of failed bushing portion, energy dispersive x-ray spectroscopy (EDS) analysis, Chemical composition analysis using optical emission spectroscopy (OES), 3D Simulation of Electrical Stress on 245 kV draw lead (Flexible Conductor) oil impregnated paper (OIP) type condenser bushing and average viscometry degree of polymerization on failed bushing's cellulose paper. R phase HV side 245 kV OIP bushing of an

interconnecting transformer got failed at Jharkhand, India in the season of winters and in the month of November as show in figure 1. Failure was noticed as 220 kV/132 kV 250 MVA transformer got tripped due to differential protection and Buchholz trip.

Abnormality was noticed just before this above incidence where B phase lightning arrestor failure on Low voltage (LV) side was noticed 2 days before. Transformers were in operation for 15 years with around 20 charging and discharging events with no prior history of fault. Just prior to fault, current on HV side was 190 A where HV bushing which got failed was designed to operate for 800 A and LV side was 320 A. Tropical climate is observed at site throughout the year with expected life of 30 years of HV bushings in this weather condition. HV tan delta test was done 1 year back prior to this failure in the last scheduled outage where $\tan \delta$ was reported 0.298 % and capacitance of the bushing was 340.27 pF.



Figure 1: Site photo depicting tilted R-phase failed HV transformer bushing.
Source: Author, (2026).

II.1 VISUAL OBSERVATION

A visual examination of failed bushing components was carried out as shown below in figures 2 to 5. The bushing was dismantled and insulation layers were unwound carefully as shown in figure 4. The tap portion was found intact, and no burn of flashover was observed in this region. Insulation paper was found burnt almost at the center of the bushing. All the damage was localized at that location as shown in figure 2. Burn marks were seen only on top layer of insulation throughout the length of the bushing. Except at the burn portion (at center) all internal layers were found normal. The draw lead was found to have burnt strands and got open circuited (almost 70% strands open) as seen in figure 2. The burnt lead position coincides with the burnt paper location. The burnt portion is nearly one foot above from the lead joint. Insulating paper layers were removed gradually. Oil traces were found in all layers throughout the length of the bushing, indicating that bushing was not dry in any region during its service. Aluminum foils used for voltage grading were found to be intact at all locations and hole size was gradually reduced as observed during unwrapping. A hole of 2cm diameter approximately was found on the aluminum tube as shown in figure 5. The burnt location coincided with the burnt copper strand location in the draw lead. The aluminum tube was cut open at the fault region for closer internal examination.



Figure 2: Failed 245 kV Condenser bushing with displaying a failed Draw Lead in the bottom of the picture.
Source: Author, (2026).



Figure 3: Site photo depicting tilted R-phase failed HV transformer bushing.
Source: Author, (2026).

Burn and overheating/pit marks, were seen all around the tube inside. Reduction in thickness was observed in a few locations, similar to prolonged overheating. Internal of the rest of the tube was found normally by visual examination as well as in borescope inspection. During the process of removal of the defective bushing from the transformer, it was seen that the bottom porcelain had broken and fallen inside the tank. There were superficial burn marks and cuts on the bottom paper insulation as shown in figure 3. The top cap of the bushing got dislodged from its cementing portion and hot oil/gases escaped from it. Burnt paper was projecting out of the top opening. R phase winding lead clamps, holding the winding lead between the winding exit and the bushing, were found broken and the lead was found freely moving. There were signs of pressure at the lead exit point and the strands got disturbed from the original location and the paper insulation was found torn.



Figure 4: Radial Breakdown of bushing paper near the bushing flange.
Source: Author, (2026).

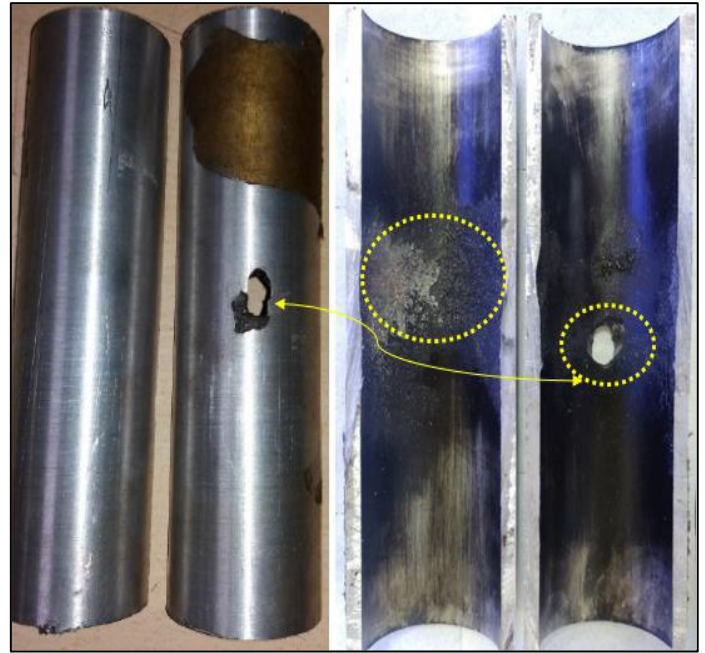


Figure 5: Burn marks inside the AL tube.
Source: Author, (2026).

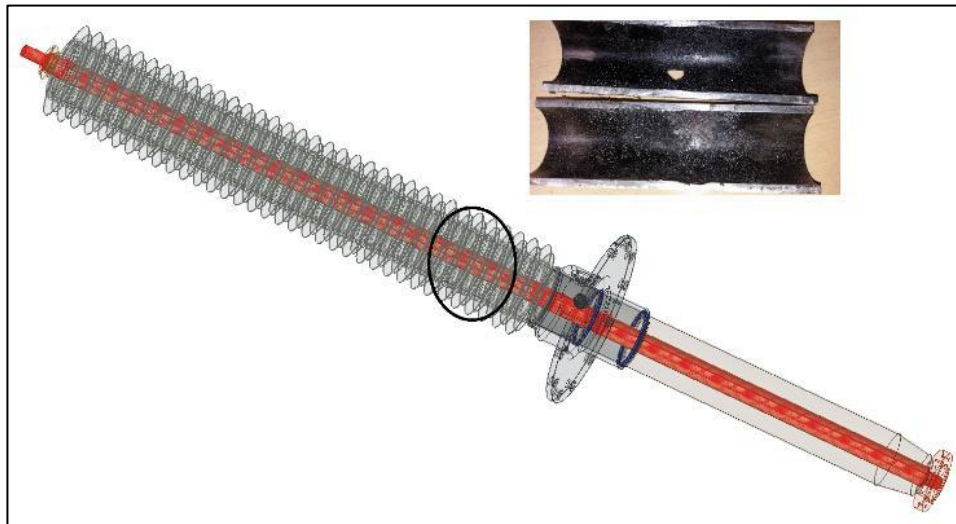


Figure 6: Fault location inside condenser bushing.
Source: Author, (2026).

Failed aluminum tube showed presence of fracture void near the flange along the thickness of tube as shown in figure 6. Internal view of tube showed rough surface (melted region) opposite the fracture void surface.

II.2 MACROSCOPIC EXAMINATION

Macroscopic examination of surface near the fracture void indicated the presence of shiny orange particles (melted copper attached to the aluminum tube surface) as shown in figure 7. Void formed due to melting of copper strands opposite to fracture surface and the droplets of fluid copper flowed into the aluminum tube. Grooves were observed when seen from the cross-sectional view of the fracture void which was due to liquid flow of the copper droplets. Fracture void was seen at an inclination along with the thickness of the fracture which was due to the installation of bushing at an inclined angle as shown in figure 8.

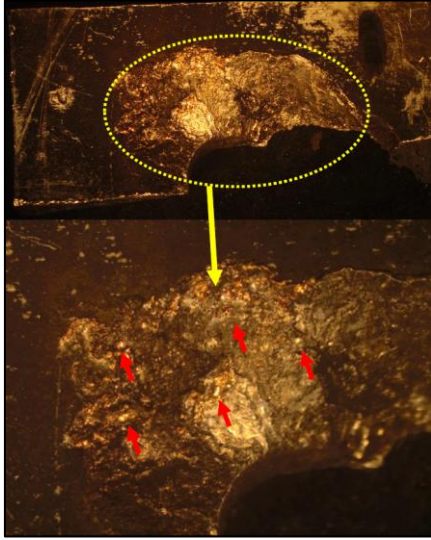


Figure 7: Macro structure of void of aluminum tube with zooming of cross-sectional surface (6x magnification).
Source: Author, (2026).

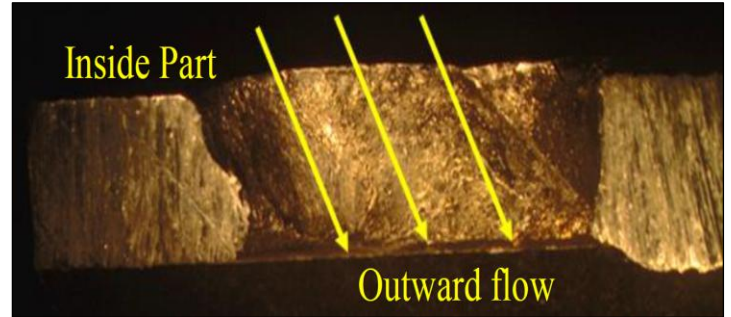


Figure 8: Macro structure of void of aluminum tube with zooming of cross-sectional surface (6x magnification).
Source: Author, (2026).

II.3 SCANNING ELECTRON MICROSCOPY (SEM)

SEM micrographs of rough region showed smooth appearance region with lot of porosity. It also showed presence of smooth melted and solidified portions on rough surface. Inside fracture void region, it showed groove lines along the thickness which was formed due to hot copper liquid flow. No signs of prolonged overheating of aluminum tube and the draw lead conductors.

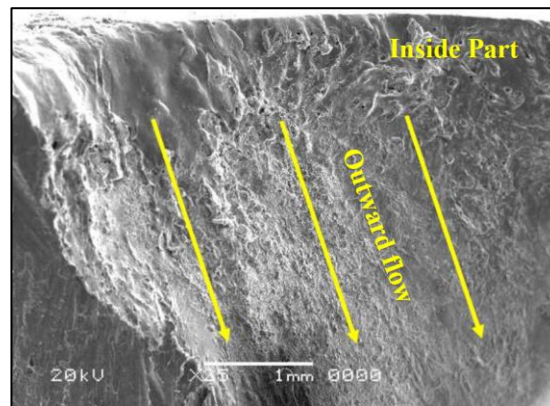


Figure 9: SEM of fracture surface of void present on aluminum tube.
Source: Author, (2026).

II.4 ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDS) ANALYSIS

EDS analysis of shiny orange particles present in rough surface and melted region was carried out to confirm the composition. EDS confirmed the presence of copper in melted regions of aluminum.

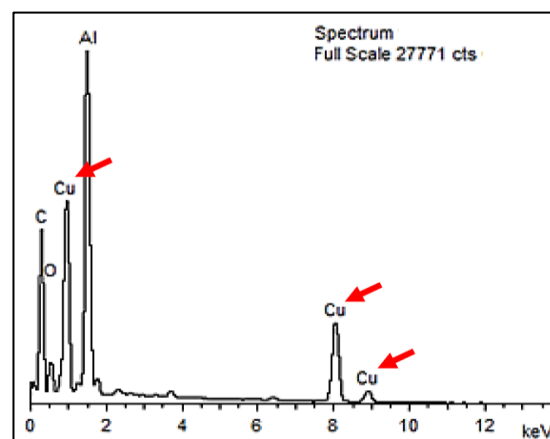


Figure 10: EDS image in rough surface and melted region in the void.
Source: Author, (2026).

II.5 CHEMICAL COMPOSITION ANALYSIS USING OPTICAL EMISSION SPECTROSCOPY (OES)

Chemical composition of aluminum tube confirms that it is an aluminum-magnesium alloy. The chemical composition analysis of aluminum tube was conducted to confirm the grade of the material. The results are given in the table below.

Table 1: Chemical composition of aluminum tube.

Elements	Obtained Value [% wt.]
AL	72.743
MN	26.632
Miscellaneous	0.625

Source: Author, (2026).

II.6 3D SIMULATION OF ELECTRICAL STRESS ON 245 KV DRAW LEAD (FLEXIBLE CONDUCTOR) OIP TYPE CONDENSER BUSHING

Authors were interested in finding the maximum electric field in the 245 kV draw lead-flexible conductor OIP bushing. Hence finite element method based electrostatic analysis was chosen where the solver computes static electric fields of a stationary object. 3D object creation, material definition, boundary conditions and voltage excitation were carried out. During modelling of 245 kV OIP condenser bushing, the components mentioned in table 2 were worked out with high precision using Finite element method (FEM) based software tools. Electric scalar potential is solved in electro-static FEM simulations where electric field and electric flux density are calculated.

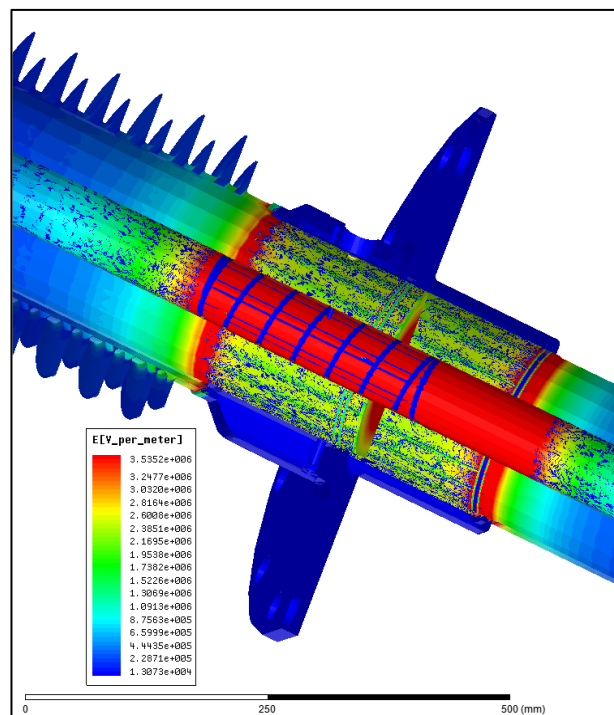


Figure 11: Electrical Stress Distribution (cross-section).

Source: Author, (2026).

All conductors are assumed perfect where joule losses are considered zero. Relative permittivity and bulk conductivity are defined for each component as shown in table below.

Table 2: Material Parameters taken into consideration in simulation.

Sr. no.	Component	Relative Permittivity	Bulk Conductivity (Siemens/m)
1	OIP Insulation	3.9	0
2	Flange (mild steel)	1	2000000
3	Housing (Porcelain)	5.7	0
5	HV Conductor (Aluminum tube)	1	38000000
6	Draw Lead (Copper)	1	58000000

Source: Author, (2026).

Ground potential is applied to flange area, and 245 kV voltage has been applied to HV conductor as a known potential. Electrical stress is seen maximum near the flange area.

II.7 AVERAGE VISCOMETRY DEGREE OF POLYMERIZATION (DP) ON FAILED BUSHING'S CELLULOSE PAPER

DP values indicate 'new' health of paper sample collected from the healthy part in the failed region and 'good' health of paper samples collected from the failed region.

Table 3: DP Test results of failed bushing's cellulose paper.

No.	Paper Sample	DP Value obtained
1	25 m (outside to inside)	1195
2	150 m (outside to inside)	1124
3	1110 m (outside to inside)	1107
4	Healthy part of failed portion	1052
5	Failed portion	733
6	Failed portion (Extremely burned)	733

Source: Author, (2026).

III. FAILURE MECHANISM

A radial breakdown near the bushing flange with intensive thermal degradation of insulation near that region was seen in visual inspection. After opening of bushing, fracture void on the central aluminum tube in the breakdown region was seen along the tube thickness. Fault recorder data showed incipient faults in the transformer. There was a Lightning arrestor (LA) failure on LV side 24 hours prior to this bushing failure. In macroscopic examination, fracture void was observed at an inclined angle along the thickness of the fracture which was due to the installation of bushing at an inclined angle. Groove lines were detected due to hot liquid flow from inside to outside the bushing in SEM analysis. EDS confirmed the presence of copper on melted regions of aluminum in the breakdown region. DP values indicated good health of paper samples collected from the failed region. FEM suggested that maximum electrical stress in near flange area. Seeing all the above observations, it leads us to one conclusion that this is a thermal type of failure of this 245 kV condenser bushing which happened in the current path of the condenser bushing. Very Fast Transient (VFT) played a certain role in the development of this failure scenario [4]. As shown in figure 12 below, during the occurrence of VFT drastic rise in voltage drop caused voltage difference between the draw lead and the central tube from top connection to bottom connection [5].

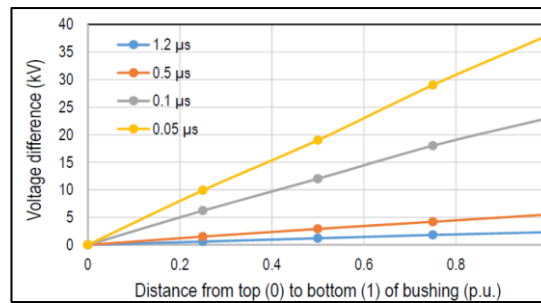


Figure 12: Voltage difference between draw lead and central tube during VFTs.

Source: Author, (2026).

Normally the VFT ends at the terminals but in this case, due to the 'in-between contact' of tube and draw lead near the bushing flange, VFT ended at the in-between contact near the bushing flange which created a punch hole type fracture void in the aluminum tube [6]. Melting of copper strands clearly shows that temperature inside the aluminum tube might have gone above 1085°C (Melting point of copper). Due to cooling being difficult in the flange region, intensive thermal degradation was seen near that region only and not causing harm to any other areas. Consequence was finally a radial breakdown near the bushing flange. This clearly showed how an incipient failure of HV transformer developed into a terminal failure. However, analysis of bushing oil after failure could not be carried out due to non-availability, which may have provided us with additional information about the presence of arcing and overheating.

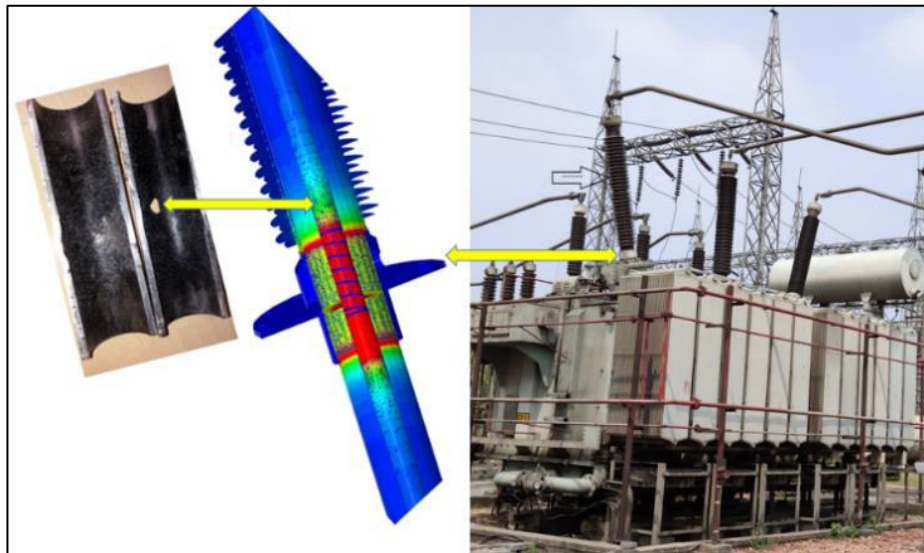


Figure 13: Failure Mechanism in presence of VFT.

Source: Author, (2026).

IV. REMEDIAL MEASURES

Improving the dielectric strength of the insulation between the copper draw lead and the central aluminum tube will help to minimize the risk of such failure scenario. 1 mm of thermally upgraded insulation between the draw lead and central tube should be suggested to the manufacturer for such type of flexible conductor design for titled bushings. This would ensure that there is no ‘in-between contact’ between the draw lead and aluminum tube which provides sufficient ‘in-between’ insulation during such sudden rise in voltage drop situations from top to bottom of the bushing [5]. The most effective in-service mitigation measure for this failure scenario is bushing thermal image scanning [7]. When a problem is suspected (especially in the case of draw flexible lead with tilted bushings), DGA (bushing oil – if appropriate) may provide additional information about the presence of any arcing or overheating [8], [9].

V. CONCLUSIONS

Based on the above failure case study, a transformer bushing must be replaced before it fails when it no longer meets the requirement of reliability. This needs a bushing asset health review methodology to analyze and prevent such in-service failures. This involves using information from wide ranges of sources which includes thorough visual inspection on daily basis, bushing oil tests, on-line and offline diagnostics tests and condition assessment after that. In addition to this, knowledge of transformer bushing designs and of their strengths and weaknesses is very vital to understanding other information. The above example illustrates how incipient failures could be managed and could be even saved by effective design reviews before manufacturing combining with effective online diagnostics and offline condition monitoring tests and assessment.

VI. AUTHOR’S CONTRIBUTION

Conceptualization: Sagar Bhutada.

Methodology: Sagar Bhutada.

Investigation: Sagar Bhutada.

Discussion of results: Sagar Bhutada.

Writing – Original Draft: Sagar Bhutada.

Writing – Review and Editing: Sagar Bhutada.

Resources: Sagar Bhutada.

Supervision: Sagar Bhutada.

Approval of the final text: Sagar Bhutada.

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