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A New Criterion for Optimal Dielectric Design of High Voltage Bushing Internal Shields in Large Power Transformer

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Abstract

The High Voltage (HV) bushings are the most sensitive components of power transformers, they provide electrical insulation between the HV line and grounded tank, and also provide necessary mechanical support. The majority of transformer breakdowns are attributed to the HV bushings failures which are graded with conductive layers to improve their dielectric strength. The design of bushings is quite challenging with tradeoff between the axial and radial electric stresses. The bushing design is also governed by its mounting angle and transformer tank configuration to meet the internal and external flashover clearances and creepage requirements. At higher voltage levels, the configuration of HV bushing shield and grounded structural components have significant impact on dielectric withstand strength other than the clearances. Hence, it is very important to study the electrode configuration inside transformer tank for a particular bushing mounting arrangement before finalizing the bushing internal shield design. The 3D electrostatic field analysis of high voltage generator transformer was carried out for different bushing shield configurations to evaluate the electric stress distribution and the dielectric breakdown strength of the equipment was verified experimentally. The authors recommend to study the dielectric design of transformer in tandem with transformer configuration and a new evaluation criterion for optimal design of bushing internal shield is proposed.

Keywords: Bushing, Clearances, Dielectrics, Shields, Transformers

1. Introduction

High voltage bushings provide the mechanical support and electrical strength for the lead take out of transformer, by providing necessary insulation from grounded enclosures. The design of insulation for a particular configuration is based on test voltage levels, dielectric strength of insulation, clearance between HT and LT and shape of the electrodes. The dielectric withstand strength for a particular configuration can be improved by providing appropriate clearances and shield of optimal dimensions, which minimizes the non-uniformity in electric field distribution.

Insulation is the heart of transformers and it is very important to ascertain the design adequacy of its insulation at the design stage itself, failure of transformer on test bed is of a serious concern, as it involves financial implications not only by damaging the material employed but also the manufacturing cycle time. The conventional design guidelines are based on experience gained and empirical formulae based on 2D calculations. For higher voltage class transformers with non-uniform electrode configurations the 3D electric stress values differ substantially from the 2D values. Hence, it is very important to review and improve upon the existing design guidelines for varying voltage levels and electrode

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configurations, to minimize the transformer failures on the test bed and also improve the reliability of equipment.

Electrode configurations with extremely non-uniform fields are more common in practice than with uniform and weakly non-uniform fields. The joint between the HV line lead and bushing draw lead is very critical and should be given adequate fastening and support. Electrostatic shields are arranged over this contact region to minimize the stress in this critical zone. The bushings are mounted at an angle on the transformer tank to achieve the required clearances between the external lines connected to grid, while maintaining minimum clearances inside the tank. The stress shield is considered as an integral part of the bushing assembly. An optimal design of bushing bottom shield is very important from the dielectric design clearances point of view, shield of smaller diameter may not minimize the stress on shield surface below the critical value, while shield of larger diameter may result in higher stress on the grounded electrode and result in breakdown of insulation[1]. Hence, it is very important to study the shield design with reference to the lead routing, winding assembly, mounting angle and tank configuration to achieve the optimal withstand strength of transformer insulation.

2. Electric Field Analysis and Bushing Design Clearances

The Transformer test bed failures are of serious concern to manufacturers for economic reasons and even minor rectification will result in substantial extension of delivery time. Detailed investigations were carried out on 400 kV generator transformer, which failed during HV tests, to review the dielectric design guidelines of HV bushings. The type of applied voltage has a direct bearing on the breakdown of insulation, hence transformers are tested with different waveforms at different voltage levels. It is very helpful for a designer to evaluate the dielectric design of transformer with reference to a single equivalent test voltage level. It is a usual practice to select ACSD power frequency test voltage as the evaluation test voltage level, which is also called as Design Insulation Level (DIL) expressed in kV (rms). The FEM model of 400 kV 270 MVA generator transformer HV side with graded bushing installation is shown in Figure 1. The model was generated with actual disposition and dimensions of bushing and structural parts and electric stress distribution is evaluated at Design Insulation Level (DIL) of 630 kV (rms). The existing design rules indicate the maximum allowable stress value on HV bushing bottom shield as 4kV/mm, and lead surface as 5kV/mm. The voltage and electric stress distribution on bushing shield for the 2D and 3D models are shown in Figures 2 and 3 respectively. The maximum electric stress on HV bushing internal shield, estimated by 2D, and 3D analysis are presented in Table 1.

Table 1. Electric stress distribution

Component	Maximum Electric Stress (kV/mm)	
	2D	3D
HV Bushing shield	3.7	5.4

The design calculations based on empirical formula estimated the electric stress on shield as 3.7 kV/mm, which is matching the 2D simulation results. The estimated maximum stress is below the allowable value of 4.0 kV/mm as per guideline, while 3D analysis estimated maximum stress of about 5.3 kV/mm, which is substantially higher than the permissible limit and also value obtained from design calculations. 2D electrostatic field computations assume that the components in the plane are infinitely long, while rotational symmetry model cannot be applied to bushings which are mounted at an angle. Therefore, for complex unsymmetrical geometry especially at higher voltage levels, the 3D electric stress values differ substantially from the 2D values. Therefore, it is very important to carry out 3D electric field analysis on transformer models to accurately estimate the stress distribution and also develop new design guidelines accordingly. With the advancements in computational tools, the electrostatic field analysis on complete 3D electrostatic model of the transformer was carried out at the design state itself and an optimized design can be developed.

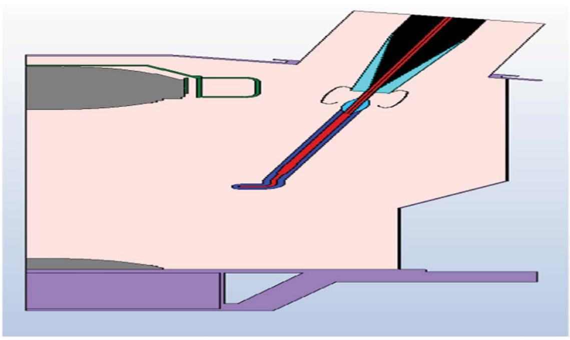

Figure 1. Loco transformer 2D model.

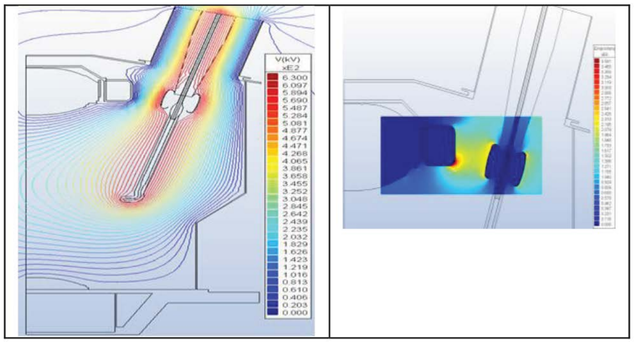

Figure 2. Voltage and stress distribution in transformer 2D model.

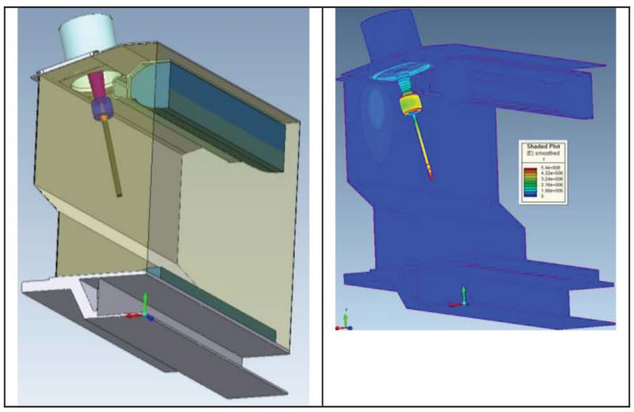

Figure 3. Electric stress distribution in transformer 3D model.

3. Evaluation of Stress Distribution along Critical Path

Parametric analysis was carried out on bushing shield diameter and it was observed that there is always a critical shield diameter for a particular clearance between bushing bottom shield and end frame at which the stresses are minimum[2]. While, for lower shield diameters the stress on shield surface is beyond allowable value and for larger shield diameters the stress on end frame was beyond allowable value.

The transformer failed under type test with flash over from bushing shield to end frame. The failed high voltage bushing was replaced with an outsourced unit with matching overall dimensions except the internal shield configuration. The transformer assembled with new bushing cleared the test. The 3D electrostatic model of the transformer with graded bushing configurations corresponding to the failed and passed units are shown in Figures 3 and 4, respectively. Detailed electric field analysis was carried out on both the models to identify the difference in electric stress distribution at all critical regions. The comparison of maximum stress in critical regions is presented in Table 2.

Table 2. Maximum electric stress on bushing surface

Component	Maximum Electric Stress (kV/mm)	
	Initial Bushing	*Replaced Bushing*
HV Bushing shield	5.4	5.8
End Frame	2.44	2.07

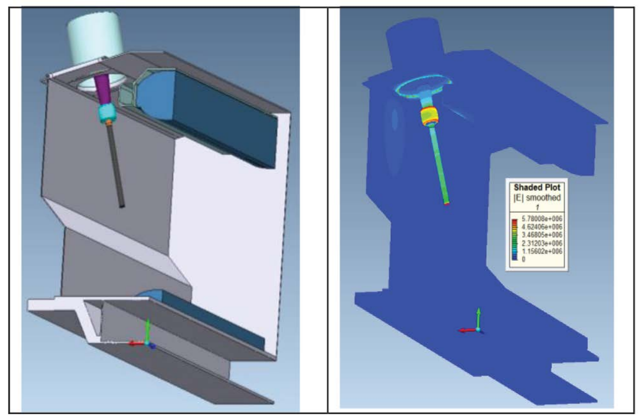

Figure 4. Electric stress distribution in transformer 3D model with new bushing.

The initial and replaced bushings have similar overall dimensions and internal insulator of 1500mm length. However, the internal shield of replaced bushing has lower diameter of about 290mm in comparison to initial bushing of 350mm diameter. From the electric field analysis, it was observed that the maximum stress occurs on bushing shield surface, which is about 5.4 kV/mm for initial bushing model and 5.78 kV/mm for replaced bushing model. While, the stress on end frame is about 2.44 kV/mm and 2.07 kV/mm for the initial and replaced bushing models respectively. It was observed that, though the maximum stress on replaced bushing shield increased due to smaller shield diameter, the stress on end frame has decreased due to increase in clearance between the shield and end frame. There is a trade-off between maximum stress on Bushing shield and end frame, and it is very important to study the maximum stress on both components and limit them within the allowable values to achieve the optimal design.

To study the effect of bushing internal shield configuration on maximum and average stress distribution in critical regions, parametric analysis was carried out on rotational symmetric model of bushing internal shield and end-frame configuration, with fixed centre to centre clearance of 425mm and variable shield diameters. The distribution of maximum electric stress for different shield diameters is shown in Figure 5. It is a general practise to increase the shield diameter to minimize the electric stress, but it may be observed from the graph that the stress decreases with increasing shield diameters up to an optimal shield diameter which offers minimum stress, beyond which the stress increases for larger diameters.

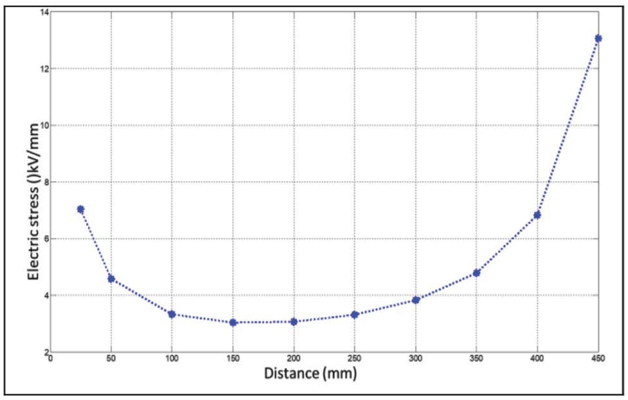

Figure 5. Electric stress for varying shield diameter.

For dielectric designs with closed boundaries and limited clearances, it is very important to study the maximum electric stress on ground electrodes along with HV electrodes. The empirical formulae do not estimate the stress on the ground electrodes, hence it is imperative to carry out FEM analysis for such configurations at the design stage itself and verify the safety margins based on the maximum electric stress estimated on the surface of live and ground electrodes. The parametric analysis of transformer bushing model resulted in an optimal shield diameter of about 250mm, for design clearance of 320mm from shield surface to end frame. The initial bushing design results in lower stress on shield surface, while the replaced bushing design offers lower stress on end frame. Further investigations were carried out to study the effect of maximum stress on live and ground electrodes and stress distribution between them on dielectric withstand strength, and develop a guideline to identify the optimal solution. The breakdown phenomena between non-uniform electrodes with relatively larger clearances is governed by the average stress in the critical breakdown region which drive the charges in bridging the gap during breakdown[3].

4. Design Optimization

The field distribution between bushing shield and end frame, in the critical plane, for transformer model with initial failed bushing is shown in Figure 6a and electric stress distribution across the breakdown path is shown in Figure 6b, and the field distribution for transformer with replaced bushing is shown in Figures 7a and 7b respectively. As discussed earlier, there is trade-off between the maximum stress on bushing shield surface and end frame, which can be gauged by the average stress calculation along with critical breakdown path. The average stress along the critical path for the initial bushing model was estimated as 2.2 kV/mm, while it was estimated as 1.96 kV/mm for the replaced unit.

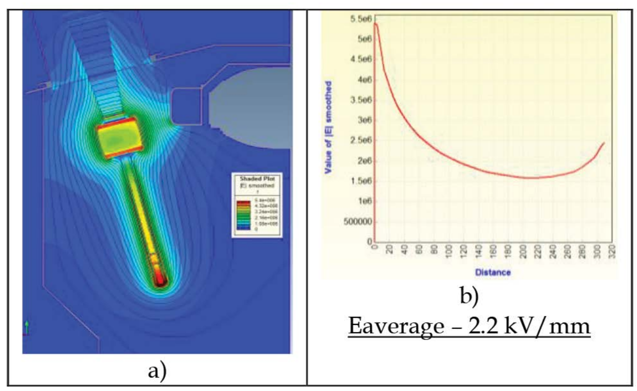

Figure 6. Electric stress distribution from live shield surface to grounded end-frame.

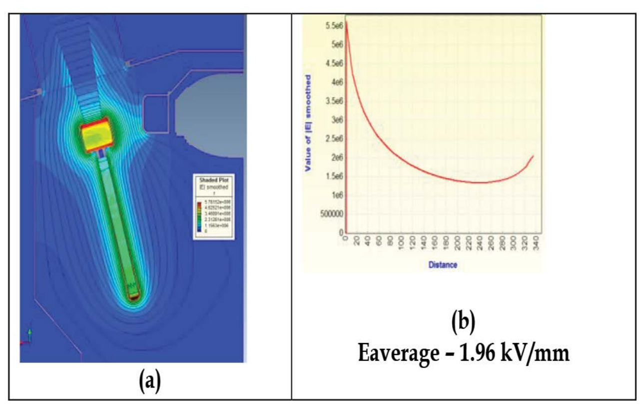

Figure 7. Electric stress distribution from live shield surface to grounded end-frame.

The maximum electric stress, on both bushing internal shield and yoke end frame, cannot be minimum for a particular configuration. The stress on shield surface decreases while stress on end frame increases marginally with increasing shield radii up to a limiting value, beyond which the stress on end frame becomes higher than the value on shield surface, leading to breakdown. The stressed volume theory is based on similar phenomena[4], where in the dielectric strength of the insulation system reduces with rise in stressed oil volume. If the electrode radius is increased the stress values reduce, but at the same time the stressed oil volume increases reducing withstand. Hence, the optimum electrode contour can be determined by studying the relative variation of stress and strength due to the changes made in the electrode contour[5]. Accordingly, further optimization was carried out and bushing with internal shield of 250mm diameter was finalized, considering the minimum average stress of 1.85 kV/mm along the critical breakdown path and limiting the maximum stress on shield surface to 6 kV/mm as indicated in Figure 8.

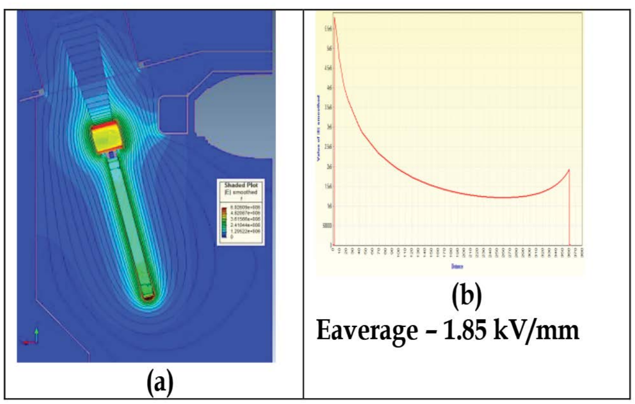

Figure 8. Electric stress distribution from shield surface to end-frame for the optimal configuration.

Therefore, estimation of average stress is a good guiding tool, to determine the optimal configuration. The replaced unit has substantially lower average stress in comparison to original unit and thus offers maximum withstand strength. The simulation results are matching the experimental results. The design optimization was carried out to achieve the required dielectric strength based on average stress calculations along the critical breakdown path and the final model cleared all the HV tests.

It is not only important to accurately estimate the electric stress distribution but it is also important to limit the maximum stress on electrodes to 6 kV/mm and average stress along the critical breakdown path below 2 kV/mm. The test results substantiate the proposed hypothesis. Further investigations are being planned to establish the (allowable maximum and average stresses in the critical regions) relevance between average stress in the breakdown region and design clearances for high voltage equipment.

The economical design of transformer requires optimal design of bushing with reference to the tank configuration, lead routing, winding and end frame. The design of transformer or bushing in isolation, without considering the effective clearances between live and ground parts with reference to mounting configuration, cannot provide optimal solution. Based on the investigations carried by the authors it is recommended to study the dielectric design of transformer in tandem with bushing configuration and evaluate the design based on the proposed evaluation criteria.

5. Conclusions

Insulation is the heart of transformers and it is very important to ascertain the design adequacy of its dielectric strength at the design stage itself. With recent failure of transformer bushings, detailed investigations were carried out to evaluate the safety margins of bushing bottom shield configurations and review the existing design guidelines. A comprehensive study on the effect of different electrode configurations and dielectric clearances on the withstand strength of insulation system was carried out, and the safety margins with reference to electric stress distribution was evaluated.

Parametric analysis was carried out on bushing internal shield dimensions of 400 kV transformer and it was observed that there is trade-off between the maximum stress on internal shield and end frame, and it was observed that average stress distribution in the critical breakdown path also plays an important role in breakdown of insulation. The design optimization was carried out to achieve the required dielectric strength of transformer based on calculation of average stress along the critical breakdown path and maximum stress on bushing shield surface. The final design with proposed configuration cleared the required tests. Further investigations are being planned to verify the application of proposed method for other configurations.

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7. References

1. Ryan HM. High voltage engineering and testing; 2001. p. 744. https://doi.org/10.1049/PBPO032E
2. Kato K, Han X, Okubo H. Insulation optimization by electrode contour modification based on breakdown area/volume effects. IEEE Transactions on Dielectrics and Electrical Insulation. 2001; 8(2):162-167. https://doi.org/10.1109/94.919913
3. Kuffel E, Zaengl WS, Kuffel J. High voltage engineering fundamentals; 2000. p. 225.
4. Kulkarni SV, Khaparde SA. Transformer engineering design and practice. 8.3.5.
5. Kato K, Han X, Okubo H. Insulation optimization by electrode contour modification based on breakdown area/volume effects. IEEE Transactions on Dielectrics and Electrical Insulation. 2001; 8(2):162–7. https://doi.org/10.1109/94.919913