

On Electric Stresses at Wedge-shaped Oil Gaps in Power Transformers with Application to Surface Discharge and Breakdown

H.-Z. Ding (1), Z. D. Wang (1) and P. Jarman (2)

(1) University of Manchester, School of Electrical and Electronic Engineering
P. O. Box 88, Sackville Street, Manchester M60 1QD, UK

(2) National Grid, NG House, Warwick Technology Park, Warwick CV34 6DA, UK

Abstract- The problem of a high-voltage applied to a wedge-shaped oil gap in power transformers is considered as far as induced distortions and tangential electric stresses are concerned. Near-tip distortions and electric stress concentration occur due to the essentially difference in the relative permittivity between the insulating oil and the pressboard. When the magnitude of tangential electric stress intensity reaches a critical threshold value, surface discharge and breakdown occurs at the oil/pressboard interface. In this work, a simplified computation model is developed for the quantitative analysis of the distribution of electric stress and the breakdown electric field strength in the wedge-shaped oil gap in power transformers. The detailed computation results on the effects of pressboard permittivity and thickness on the surface discharge inception voltage are presented. It shows that the surface discharge inception voltage is a function of pressboard permittivity and thickness; and the value of surface discharge inception voltage decreases with increasing dielectric permittivity.

I. INTRODUCTION

Surface discharge and breakdown is a phenomenon that commonly occurs in the composite oil-pressboard insulation system in oil-filled power transformers [1-6], and likely one of the most dangerous failure modes that typically results in a catastrophic failure of power transformer at normal operating conditions [7,8]. The problem comes from the design of the high voltage insulation structure of oil-filled power transformers, where the withstand and the breakdown strengths of the coil section of oil-filled transformers are dominated by the partial discharge inception voltage of the wedge-shaped oil gaps that, as shown in Fig. 1, are usually made of the paper insulated conductors, mineral insulating oil and the pressboard barriers. Due to the essentially difference in the relative permittivity between the oil and the pressboard which causes the electric field stress concentration on the insulating oil gap, the wedge-shaped oil gaps are in fact the insulating weak parts in transformers [1,3,5]. When the partial discharges are caused by various factors within the wedge-shaped oil gap, these discharges will develop onto the oil/pressboard interface to initiate surface discharge under AC voltage condition. Such a phenomenon in some cases occurs continuously and causes deterioration of pressboard surface, which ultimately results in failure of transformer insulation

system. In practical insulation system, however, this is a progressive phenomenon which may not be noticed during the early stages of its occurrence due to its low magnitude.

In order to explore the quantitative description for surface discharge occurrence and development on the pressboard surface in oil, one needs to know something of the distribution of electric stress and the breakdown electric field strength in the wedge-shaped oil gap. Very little has been published with regard to the surface discharge characteristics of pressboard in transformer mineral oil. This may be because this topic almost exclusively involves very inhomogeneous stresses, and a rigorous analysis of the electric stress distribution in the wedge-shaped oil gap and particularly the tangential electric stress induced at the oil/pressboard interfaces should be based on nonlinear field theories. However, it is insightful to proceed with simpler calculations based on a quasi-uniform field in a narrow oil gap. This paper will attempt to show that a simplified computation analysis of the electric stress distribution at wedge-shaped oil gap can lead to a quantitative prediction of the relationship between the surface discharge inception voltage and the dielectric permittivity of the surrounding medium. The evidence for the validity of this relationship is discussed briefly.

II. THE MODELS

A. Determining the wedge-shaped oil gap length

Without loss of generality, a partially sphere to partially sphere brass electrode system is selected for illustrating the electric stress analysis and wedge-shaped oil gap length calculation. A cross-section of the tested electrode geometry and pressboard arrangement that is used in this study is shown in Fig. 2. The oil gap length in the wedge-shaped oil gap can be considered as the length R_{OW} in the radial direction from the surface of the high-voltage electrode, and a simple mathematical computation gives

$$R_{OW} = R \left(\frac{1}{\cos \theta} - 1 \right) \quad (1)$$

Where $R = 25$ mm is the radius of spherically-capped electrodes, and θ is the polar angle on the spherically-capped electrode counted from the symmetry axis.

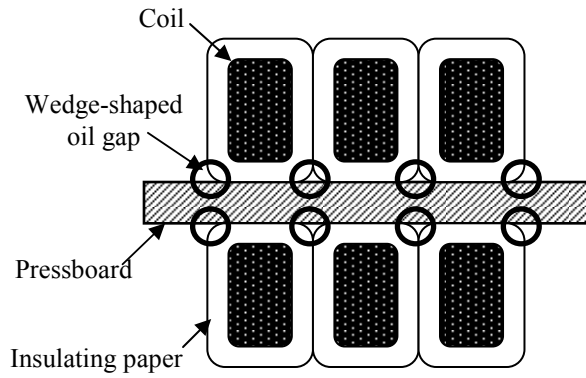


Fig. 1. Schematic description of the cross section of disc type high voltage windings and its insulating structure

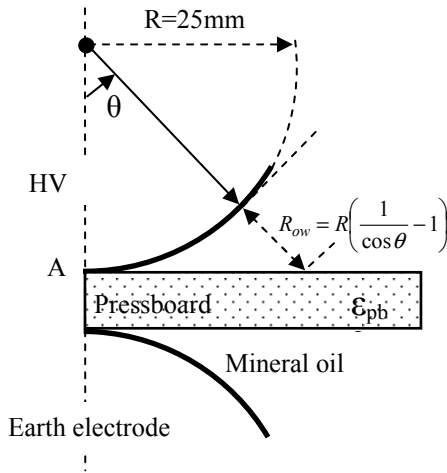


Fig. 2. Electric stress analysis and oil gap length computation model

B. Electric stress distribution within the wedge-shaped oil gap

Consider first the electric stress distribution in an oil gap only between two conductive spheres of the same radius. For a quasi-uniform field in a narrow oil gap between two spherical electrodes, the electric stress distribution on the electrode surface near the symmetry axis can be calculated approximately by [9]

$$E_{oil} \cong \frac{V}{d + 2R(1 - \cos \theta)} \quad (2)$$

Where V is the applied AC voltage, d is the oil gap length along an axis between electrodes, R and θ are the same as previously noted.

Then, with pressboard inserted between two spherical electrodes, the electric stress in the wedge-shaped oil gap will be redistributed. Numerical computations on electric field behavior at a triple junction in composite dielectric arrangements have shown that near and at the point of contact

between the electrode and the pressboard, the electric field stress can be expressed approximately as [10]

$$E_{oil, pb} \cong \frac{\epsilon_s (\epsilon_s + 1)}{2} E_{oil} = \frac{\epsilon_s (\epsilon_s + 1)V}{2(d + 2R(1 - \cos \theta))} \quad (3)$$

where $\epsilon_s = \epsilon_{pb} / \epsilon_{oil}$ is the relative permittivity.

C. Determining the breakdown electric field strength distribution within the wedge-shaped oil gap

The relationship between the oil gap distance d (mm) and the breakdown electric stress E_B (kV/mm) in the oil gap can be experimentally determined as follows [11]

$$E_B = 34.784 d^{-0.237} \quad (4)$$

Assuming that (4) is still valid for the relationship between the breakdown field strength and the gap length in the wedge-shaped oil gap. Substituting (1) into (4) derives

$$E_{B,OW} = 16.221 \left(\frac{1}{\cos \theta} - 1 \right)^{-0.237} \quad (5)$$

This is the breakdown electric field strength equation in the wedge-shaped oil gap.

III. THE RESULTS

A. Electric stress and strength distributions within the wedge-shaped oil gap

Figs. 3-5 show the electric stress distribution curves and the strength curve of the wedge-shaped oil gap as a function of the polar angle on the spherically-capped electrode counted from the symmetry axis (equivalently the oil gap width), for three different pressboard thicknesses of 3.0, 1.8 and 1.5 mm, respectively.

Partial breakdown of the wedge-shaped oil gap can be considered as occurring when the electric stress is higher than the strength of the oil. As a result, for example in Fig. 3, for applied AC voltages less than 54 kV, the strength of the oil is higher than the stress, and so dielectric breakdown of the wedge-shaped oil gap does not occur. When the applied AC voltage is increased to 54 kV, both the stress and the strength curves intersect for the first time at $\theta = 11.2^\circ$ and $E_0 = 41.16$ kV/mm, i.e. at this contact point the electric field stress is equal to the strength of the oil, so that the first partial breakdown of the oil gap occurs here. The applied AC voltage value of 54 kV can therefore be viewed as the estimated inception voltage for the occurrence of surface discharges at the oil and the pressboard interface for pressboard thickness of 3.0 mm. Further, if the magnitude of tangential component of electric field stress that results in surface discharge occurrence (due to the wedge-shaped oil gap breakdown) could be assumed as a criterion of dielectric surface strength of pressboard, then the magnitude of tangential component of

