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DEVELOPMENT OF A DESIGN METHOD FOR INSULATING STRUCTURES EXPOSED TO ELECTRIC STRESS IN LONG OIL GAPS AND ALONG OIL/TRANSFORMERBOARD INTERFACES

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Abstract

The electric strength of long oil gaps and along interfaces liquid/solid is critical for the design of insulating components in oil immersed power transformers. This paper describes a method of evaluating the electric strength of long oil gaps. The calculation is compared with test results. The method is extended to components with long creepage paths. Its successful use is shown by the example of a Faltenbalg layout for 400 kV power transformers.

1. Introduction

The knowledge of the dielectric strength of long oil gaps is essential for the proper design and dimensioning of the components for the delicate lead exit structure in oil immersed power transformers. It must be recognized that there is no comprehensive physical theory of the breakdown of insulating liquids, but industrial design curves have proved their full reliability over years. These curves cover sufficiently various factors and basic standards which influence the dielectric strength of oil/ transformerboard barrier insulation systems. They are successfully used for the layout of the insulation between windings. However their use is restricted to uniform fields only.

There is a need of designing insulating structures which are exposed to non-uniform fields with long oil gaps, consisting of transformerboard components of complex shape. Besides long oil gaps also creepage paths along insulating interfaces (oil/board) are present in lead exit structures, and the designing of such components like Faltenbalgs (bellows) has to be done very carefully. The existing stresses must be correctly interpreted (stress profiles, direction) and after due conversion they have to be compared with the design curves with much care - any error may result in a failure on the test floor or a catastrophic breakdown later in service.
A Faltenbalg provides a leakproof separation of the oil in the active part of a power transformer from the oil in the bushing turret, fig 1. This arrangement has the following advantages:

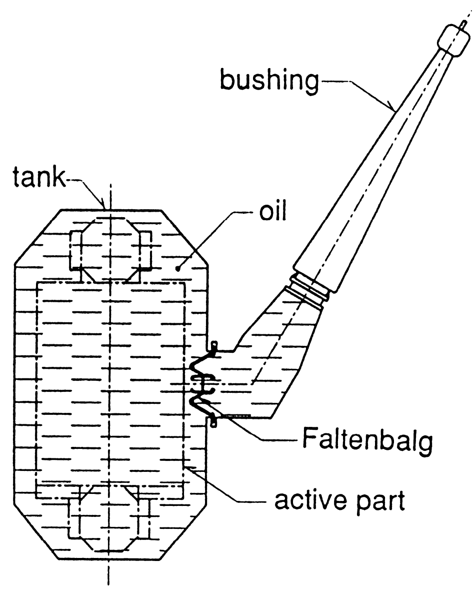


Fig. 1 Faltenbalg in an oil immersed power transformer with bushing

- The electrical connections to the bushing are made at the Faltenbalg. Therefore the active part of the transformer remains at all times immersed in oil, i.e. it has the maximum possible protection against moisture absorption and contamination.
- No connection work is necessary on the electrically highly stressed winding ends. (Short installation time).
- The transformer can be transported filled with oil if the transport weight limits do not prevent this.
- Oil handling at the installation location is limited to the small amount required to fill the bushing turrets.

Because of the particular double function of the Faltenbalg as an insulation of the HV-terminal to ground and as the partition of two oil tanks, two principle tasks with view to the electrical insulation arise:
- study of the electric strength of long oil gaps being exposed to a non-uniform field and
- study of the electric strength along the liquid/solid interface (oil/board) with variable tangential stress along the creepage path.

2. Method of determining the electric strength of insulating oil gaps exposed to a non-uniform field

Many attempts have been made to solve this problem and several authors have reported that the maximum occuring stress value will not be the only important factor for the strength of long oil gaps [1,2,3,4].

The following method is a technique whereby the known design curves for oil in uniform fields are used for determining the strength of long oil gaps in non-uniform fields. The design criterion of the method is the absence of partial discharges during the power frequency voltage test.
The stress at which partial discharge inception occurs in uniform field configurations of transformers (such as the main insulation between LV and HV winding), is strongly dependent on path length, resulting in higher permissible stress for small gaps [1]. However for many practical electrode arrangements with long oil gaps and non-uniform fields the distribution of the stress plays the dominant role. Hence in long gaps areas are allowable with a maximum stress much in excess of the average stress, as long as these areas are small.

The evaluation method compares the average stress $E_{av}(d)$ for the whole range $0 \le d \le s$ between the two electrodes along the shortest field line s with the strength curve of pd-inception of the uniform field. The result of this comparison indicates a certain critical path length d_{crit} where the limits of the strength are attained and will lead to pd inception.

The method is demonstrated by means of two similar electrode arrangements (a) and (b) and its results will be compared with laboratory measurements. The arrangement is shown in fig. 2. It consists of two parallel cylindrical electrodes of which the details are given in table 1 and fig. 4.

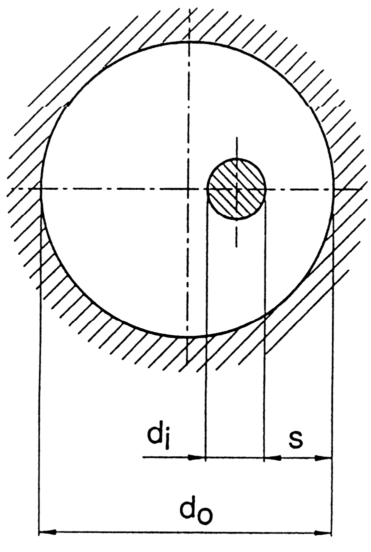


Fig. 2 Arrangement of two parallel cylindrical electrodes

	arrangement (a)	arrangement (b)
d_o	600 mm	600 mm
d_i	20 mm	80 mm
s	72 mm	72 mm
E'_{max}	4,3 %/mm	2,2 %/mm

table 1 Parallel cylindrical electrodes

E' = related stress as a result of field calculation assuming a potential difference of 100 % between electrodes

The pd inception curve in fig. 3 can be represented by E_{pd} (d) = 14.5 kV/mm · $(d/mm)^{-0,35}$, d being the gap width, [1]; the strong dependence on gap width is obvious. For arrangement (a) the related stress E'(d), determined by field plot, is also shown as a function of location in fig. 3 and the corresponding curve of the related average stress $E'_{av}(d) = 1/d \cdot \int_0^d E'(d) \partial d$ [d = 0 ... s] is added. The critical interval d_{crit} will be at the lowest point of the ratio curve $q(d) = E_{pd} / E'_{av}$. In this case d_{crit} is approximately 22 mm, the corresponding value is q_{crit} = 2 kV/%. Hence the maximum admissible voltage is determined to be 200 kV.

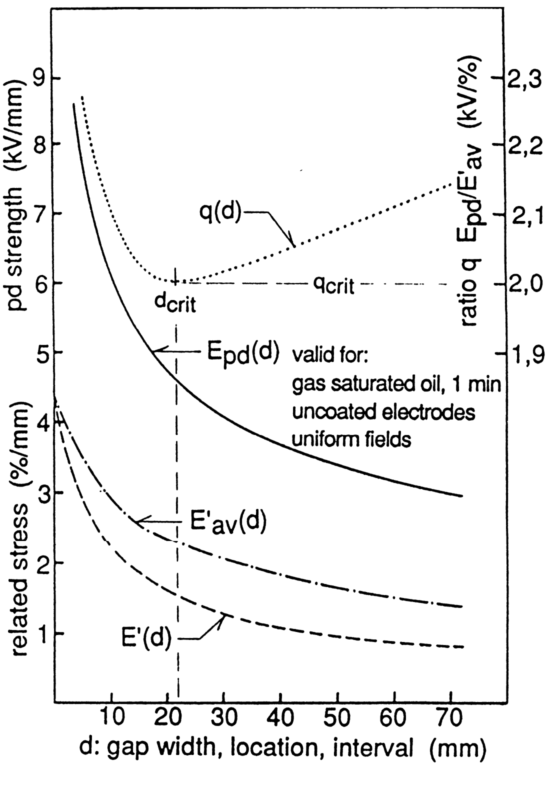


Fig. 3 Evaluation of pd-inception voltage for electode arrangement (a)

When proceeding in the same way for arrangement (b) the corresponding values are d_{crit} = 72 mm with q_{crit} = 2,1 kV/%, resulting in admissible voltage of 210 kV. Despite the fact that arrangement (b) has about half the value of maximum related stress E'_{max} (see table 1), the admissible voltage will be just about 5 % higher.

The described electrode arrangements were tested in the laboratory according to fig. 4.

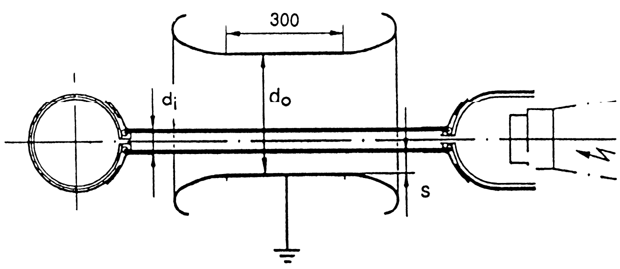


Fig. 4 Test arrangement for the laboratory experiment

Length of parallel electrodes: 300 mm
Gas saturated oil, moisture < 10 ppm
Ambient temperature
Test vessel volume: 5000 l, circulating oil
Oil flow velocity in stressed area: 2 cm/s
Applied voltage: 50 Hz continuous linear rise 8 kV/s

A large number of breakdowns have been produced and monitored: more than 40 breakdown events on each arrangement. The observed breakdown voltage values ranged from 200 to 600 kV for both arrangements. The data were evaluated according to the Weibull-distribution with excellent fitting [4]. The comparison calculated versus measured data is given in table 2.

	calculation	measurements	
	maximum voltage	voltage of 50 % breakdown probability	voltage of 2 % breakdown probability
arr. (a)	200 kV	375 kV	195 kV
arr. (b)	210 kV	420 kV	210 kV

table 2 Comparison of calculation and test results

Table 2 shows the excellent coincidence of the 2% breakdown probability values with the calculated figures. This means that the presented method suits well for designing similar electrode configurations subjected to similar test conditions, provided a 2 % breakdown probability is acceptable as an upper limit of breakdown risk.

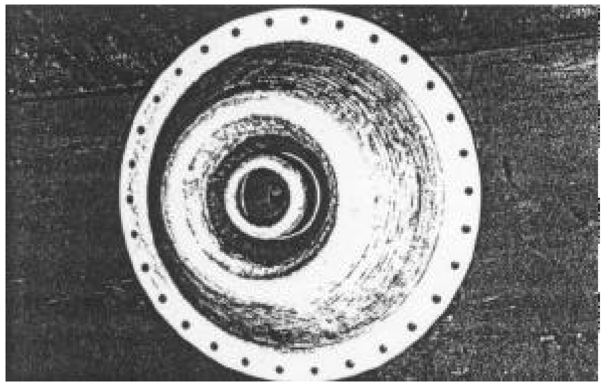
The experiment shows clearly how enormously the values of breakdown voltage are spread, which is typical for large oil gaps at power frequency voltage; the evaluation of the 50 % breakdown voltage is in fact of minor importance compared to the voltage range of low breakdown probability, because only a sufficiently low breakdown risk is acceptable for technical dimensioning.

3. Dielectric strength of long creepage paths exposed to a non-uniform field

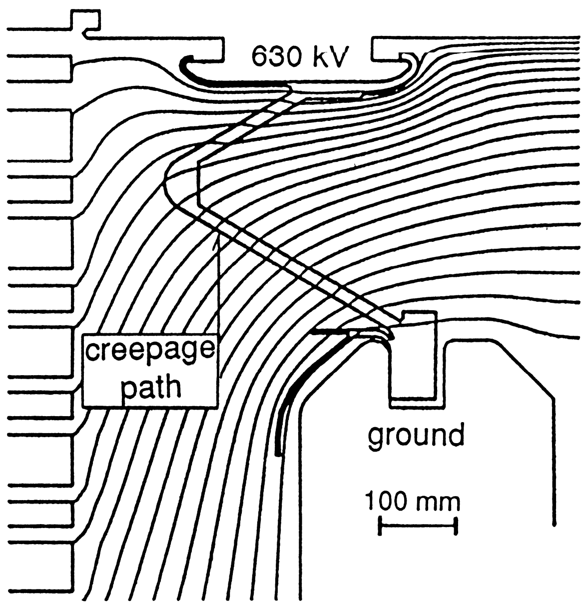
For correct dimensioning of a Faltenbalg two more problems have to be solved [5]:

- The procedure has to be adapted to non continuously decreasing stress profiles which can occur along the creepage path.
- The electric strength of the interface liquid/solid usually differs from that of the liquid itself and will depend on the surface condition.

A photograph and the electric field plot of the 400 kV Faltenbalg is given in fig. 5.



a)



b)

Fig. 5 a) Photograph of the 400 kV Faltenbalg
b) Field plot of the 400 kV Faltenbalg

The tangential stress along the surface at the one minute power frequency test voltage 630 kV phase to ground has been computed out of the field plot and drawn in fig. 6. It can be seen that the stress profile shows a large variety of values for the local stresses, and as a consequence the nature of this curve is not uniform.

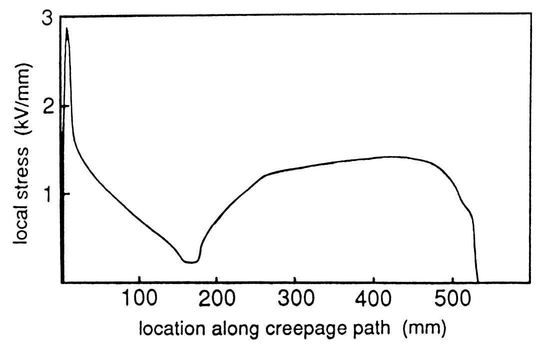


Fig. 6 Tangential stress profile along the surface of the 400 kV Faltenbalg

This curve was then converted into another one by bringing the local stress values into a new order with decreasing stress for longer paths. The highest stress is assigned to path length zero. Starting at this point the complete creepage path is scanned in the following way: all stress values are arranged in a certain order so that for selected growing path intervals d the respective highest average value found by scanning the stress profile is coordinated to the selected path interval d and plotted versus the same.

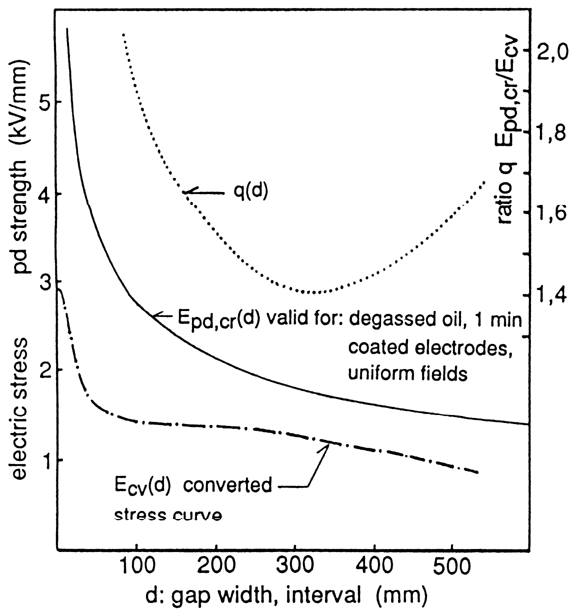


Fig. 7 Comparison of converted stress curve of the 400 kV Faltenbalg with the creepage strength design curve

The result of this conversion is plotted as $E_{cv}(d)$ in fig. 7 together with the maximum admissible design stress curve $E_{pd,cr}(d) = 15\ kV/mm \cdot (d/mm)^{-0,37}$. This creepage design curve is valid for new degassed oil and first quality transformerboard with clean surface. The graph is clearly demonstrating that the "safety factor" is higher in the area of short path intervals than in the area of longer distances. This means that the locally limited maximum stress value of 2,9 kV/mm is not as critical as the 1,3 kV/mm which prevail over an interval of approximately 300 mm along the outer wing. The lowest value of the plotted ratio curve $q(d) = E_{pd,cr}/E_{cv}$ in fig. 7 is approximately 1,4 which indicates a calculated pd-inception voltage of 1,4 · 630 kV = 882 kV.

The test in the laboratory was carried out with degassed oil and the pd-inception voltage was 950 kV. This individual test result is in good correspondence with the value determined by the presented design method.

It can be expected that a smooth and shiny surface of glazed porcelain or cast resin will be considerably reduced in its creepage strength under oil compared to oil itself since extended areas of poor interfacial contact between liquid (oil) and solid (porcelain) can be imagined. Contrary to this it is the coarse micro structure of the transformerboard surface with its local sequence of micro barriers (cellulose fibers) and micro oil gaps which grants a maximum of creepage strength as no extended interfacial contact problems are possible. This is supported by the fact that the oil is not just adjacent to the surface of the solid insulation like with porcelain or cast resin, but is filling a large number of uniformly distributed pores in the fiber matrix of the transformerboard which represent 20 % of the total volume.

4. Conclusion

The layout of a Faltenbalg for power transformers needs from the point of view of dielectric strength the application of several design criteria. Long oil gaps in combination with a varying creepage stress along the oil/ transformerboard interface must be considered. The condition of the insulating oil as well as the surface must be taken into account.
In the first section of this paper the adaptation of existing design curves to long oil gaps exposed to non-uniform fields is described and the comparison of calculation with test results is presented. The second part shows the conversion of the actual creepage stress (stress profile) into a new curve with decreasing average stress versus relevant gap width and the safety margin is easily visualized.
The appropriate use and interpretation of design curves which are commonly used for uniform fields led to the successful dimensioning of a new Faltenbalg for 400 kV oil immersed power transformers. For many other components of transformer insulation the presented design method has proven its reliability and efficiency.

5. References

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