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Experimental Evidence of Transformer Insulation Design Methods

D.J. Tschudi, K. Schultz
H. Weidmann Ltd
Switzerland

T. Prevost, W. Ashton
EHV Weidmann
USA / Canada

M. Franchek
Weidmann Technical Services
USA

Abstract

This paper investigates the dielectric properties of transformerboard / oil interfaces as found in oil-immersed power transformers and relates it to design criteria. A large number of breakdown tests were performed on a barrierboard-like insulation structure with a varying gap distance of 25, 40 and 80 mm. Test data were evaluated applying statistical methods and the best estimates of the distribution functions according to the max. likelihood criteria were calculated. The results of these experiments were compared to the state-of-the-art design methods of oil / transformerboard insulation systems. The basis of these methods, so called oil- (design-) curves are reproduced by the experiments thus proving their validity.

1. Introduction

In order to reduce the impact of a failure in the tapchanger of a power transformer some utilities specify a separation of the tapchanger from the transformer main tank (Fig. 1). With the tapchanger separated from the transformer tank maintenance as well as repair is facilitated and monitoring (e.g. DGA) can be performed inde-pendently. Furthermore, decomposition products produced by the switching operation of the tapchanger will not contaminate the oil in the main tank.

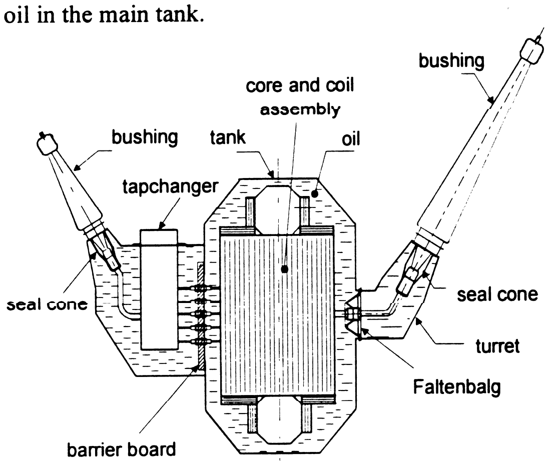

Fig.1 Schematic view of an auto-transformer with barrier board and other oil / board interface structures (Faltenbalg, seal cone) which are exposed to high levels of electric field tangential to their surface.

The connections from the transformer to the tapchanger are realized by passing the high voltage leads through connectors fixed in a rigid plate separating the main tank from the tapchanger compartment. For this application a so-called barrier board made of laminated transformerboard with integrated plug-and-socket-type terminals was developed (Fig. 2). Depending on the actual voltage of the transformer and the number of regulating steps, the clearance between the terminals is typically in the range of 20 to 150 mm.

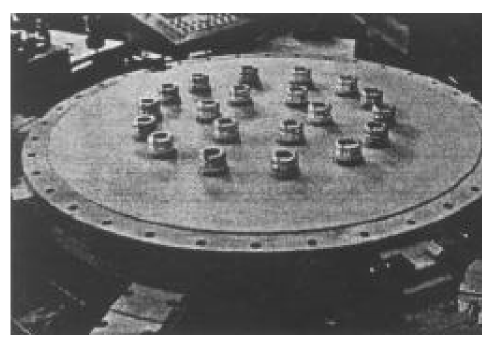

Fig.2 Typical barrier board during the manufacturing process. U_{BIL} = 850 kV, I_N = 1500 A. The barrier board is used as separating element between tapchanger compartment and transformer main tank.

The overall electric withstand strength of oil insulated systems can be improved if long oil gaps are subdivided into smaller gaps [1]. This technique which has been used for decades is chiefly applied for the main insulation and the winding end to yoke insulation of transformers where the subdivision is made with cylinders, caps or angle rings made of transformerboard. Yet, supporting components (barrier boards, clamping structures, Faltenbalgs, etc.) entail uninterrupted interfaces across oil gaps of long distances which are exposed to high levels of electric field tangential to this interface. To design such components, in analogy to the design of barrier insulation systems, so called oil curves are used linking an oil gap (or interface path) width with the level of the electric field component which is tolerated. In order to build and use barrier boards efficiently, knowledge about the permissible levels of the electric field is essential.

2. Design criteria of oil / transformerboard interfaces

In oil / transformerboard structures the breakdown is predestined to initiate in the oil as the specific withstand strength of oil is lower than that of board. Furthermore, due to the ratio of permittivities ($\varepsilon_{board} / \varepsilon_{oil} \approx 2$), the AC field concentrates in the oil and reduces stress in the board accordingly. Several attempts have been made to explain the oil breakdown mechanism [2]. However, no general model of oils used in transformers exists yet covering the various physical mechanisms leading to a breakdown. For this reason semi-empirical methods, which have been developed over years, describing the observed „macro"-characteristics of the dielectric fluid are used as a basis of design.

Kappeler [3] has observed with laboratory experiments that the breakdown strength of an oil gap, expressed in kV/mm decreases exponentially when the gap width is increased. Oil curves were derived from these experiments and were found to be suitable (through prototype tests of insulation setups) for the design of transformer insulation configurations. These curves express the maximum admissible design value as a value of low probability of partial discharge (PD) inception. Transformed in logarithmic coordinates these curves yield straight lines (e.g. Fig.7). Its ordinates for a specific oil gap vary in function of oil parameters. For solid / liquid interfaces the ordinate is reduced by about 30% to account for interface related effects.

To design such an insulating structure a field plot is calculated and evaluated. The decisive criterion is the oil path which exhibits the smallest margin between the prevailing mean electric field across the path and the admissible value derived from the corresponding oil curve.

Further design fundamentals to be used for the conception of insulation system containing solid / liquid interfaces are described in [4] and [5].

3. Barrier board

A typical execution of a barrier board with self-arresting sockets is shown in Fig. 2. The taps are covered by a sleeve made of transformerboard of which the function is to improve dielectric behaviour and secure oil tightness around the taps.

The insulation structure of a barrier board is subjected to a combination of surface stress and long oil gap stress in a moderately non-uniform field configuration. With the large number of taps operating at different voltage levels, an efficient arrangement of terminals is sought for to result in a voltage distribution (during test and operation) between terminals with minimal levels of electric stress.

The breakdown behaviour of oil / transformerboard insulation system in general is characterised by a large statistical spread. Breakdown tests to define design parameters have to reflect this fact. The low probability breakdown voltages (design values) can therefore be estimated with a large number of breakdown values only.

4. Test arrangement

In order to establish a statistically significant and reliable basis to establish design parameters of barrier boards, a suitable test arrangement was designed which permitted a sufficiently high number of experiments to be conducted in a short period of time. The arrangement consisted of a turntable on which 16-30 (depending on clearance) terminal electrodes are mounted in a circle (Fig. 3).

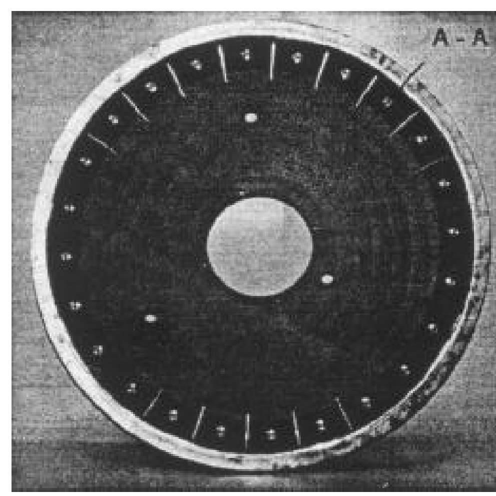

Fig.3 Turntable (∅ = 1200 mm) with terminals used for breakdown tests on a configuration similar to a barrier board. Clearance between energised terminals and flange: 40 mm.

A cross-section of the configuration is shown in Fig. 4. By turning the disk stepwise after each flashover, one terminal after another was energised with increasing voltage until a breakdown occurred to the grounded outer flange. The whole set-up was immersed in a 12 m³ tank filled with transformer oil and energised through an oil / air bushing. In order to reduce the contamination of the oil due to flashovers it was continuously circulated through a filter. Prior to the tests the disks were impregnated and the oil processed according to standard procedures.

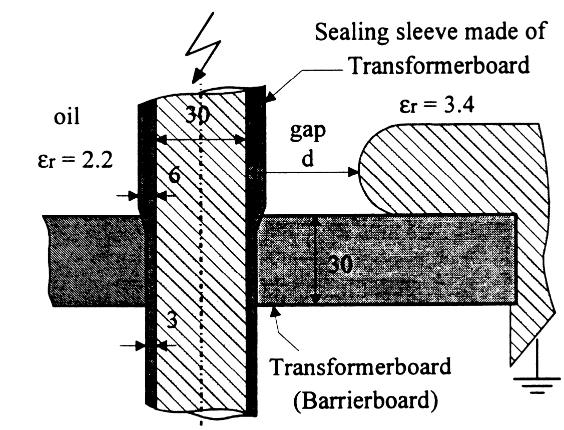

Fig.4 Cross sectional view of energised terminal and grounded flange A-A.

5. Test procedure

Three different gap widths, 25, 40 and 80 mm were examined. Depending on the gap width, a total of 48-60 terminals were tested in a 50 Hz / 1 min test (step by step voltage rise) and a standard lightning impulse test. The partial discharges (PD) at AC were measured as the voltage was risen to breakdown. Independence tests were performed on the data as the test series progressed. The condition of the oil was evaluated before and after each test series, checking the following parameters: breakdown voltage according to IEC 156/63, gas and water content, number of particles. This ensured that no significant deterioration of the oil took place during the tests. Afterwards, the disks were examined and the carbonised flashover tracks recorded, categorised and correlated with PD-inception and breakdown voltage.

6. Test results

Breakdown voltages were then evaluated statistically. For breakdowns of oil / paper insulation systems in moderately non uniform fields the Weibull distribution is the best function to describe the behaviour at low probabilities [6]. The distribution can be characterised by 2 or 3 parameters : the slope δ, the 63%-quantile η and for the 3 parameter distribution the threshold level U_0.

Because the estimate of U_0 with the present number of data is too inaccurate and may obscure incidents at low breakdown voltage occurring with low probability, the 2 parameter Weibull distribution (η and δ) is chosen. Further the 90% range of confidence is estimated (Fig. 5).

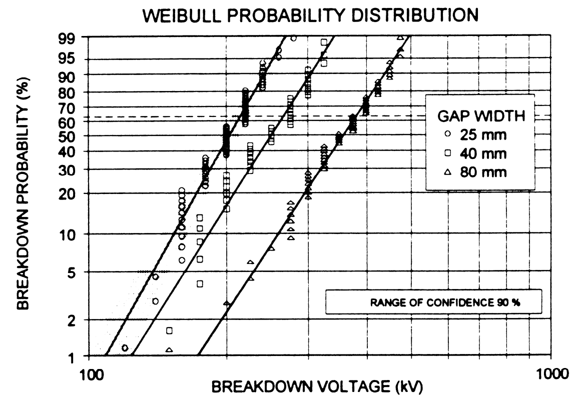

Fig.5 2-parameter Weibull plot originating from the respective breakdown voltages (50 Hz / 1 min. step by step) of the experiments (3 different gap widths). Confidence limit: 90% calculated for 25 mm gap only.

The statistical spread (expressed in the slope δ) of the experiment with gap width 25 mm is smaller (by 12%) than the spread of the two others which are within +/-3% identical. However, the 90% confidence range of the 25 mm experiment admits the possibility of a spread of the same value as the two others.

7. Discussion

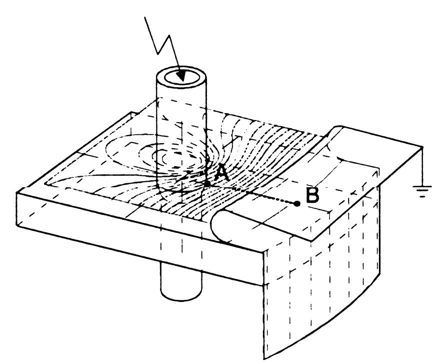

Fig.6 Field plot of tested arrangement (see Fig. 4, d = 25 mm) with 5% equipotential lines.

In order to compare the results of the experiments with the design criteria field plots of the tested configuration have been calculated (Fig. 6) and evaluated (Fig. 7). It was found that the most critical gap, defining the breakdown behaviour of the insulation configuration, was located within the distance between the insulated terminal and the grounded flange along the surface of the transformerboard plate (Fig. 6 distance A-B).

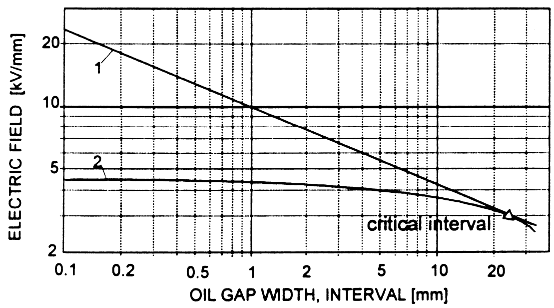

Fig.7 Evaluation at AC along the most critical path (Fig. 6, A-B) and determination of the corresponding value of the electric field. Curve 1: max. admissible stress (oil curve). Curve 2: converted stress profile at 63% breakdown voltage; originating from the value of the local electric field along the interface from point A to B (Fig. 6) and related to the respective oil gap / interface path.

The mean value of the electric field along the critical path was then calculated for the 63%-breakdown voltage of the 50 Hz and the BIL test (see example Fig. 7, results E63% 50 Hz and E63% BIL in Fig. 8). The 63%-breakdown value was chosen, because it can be estimated with a high precision for the Weibull distribution.

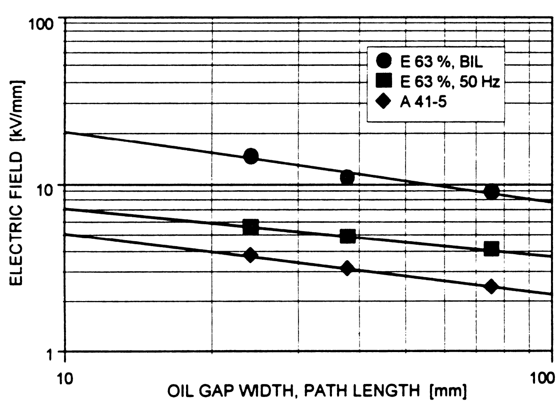

Fig.8 Mean values of electric field in function of the critical path length for 50 Hz (E63% AC) and BIL-impulse (E63% BIL) voltage at 63% breakdown probability (for experiments with gap width 25, 40 and 80 mm) and typical values of an oil curve (A41-5).

Fig. 8 shows the resulting data coordinated with the respective critical path length. Also, the corresponding values of an oil curve (A41-5) is shown. The straight lines fitted through the calculated data points yield curves almost parallel to the design curve. The maximum deviation is for E63% AC : 5% (ref. data point near 40 mm) and for E63% BIL : 8% (ref. data point near 80 mm).

8. Conclusion

Breakdown tests have been conducted for a barrier board-like insulation structure with applied 50 Hz and BIL-impulse voltage. The statistical evaluation of the tests has revealed that the electric field values considered to be the most critical by the applied design methods and attributed at the respective 63% breakdown voltage followed a similar characteristics as the typical oil (design) curve. Further the statistical spread on the breakdown values for these experiments can be regarded as equal considering a 90% range of confidence. Therefore, the low probability breakdown values which may be used to design such insulation structures will also show characteristics parallel to oil curves.

Thus it can be concluded that barrier board-like insulation structures containing oil / transformerboard interfaces bridging the insulating oil gaps can be designed with oil curves generally used for Hi-Lo gaps and winding end to yoke barrier insulation.

9. References

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