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INSULATION OPTIMIZATION OF POWER TRANSFORMER LEADS

SUMMARY

Power transformers reliability, amongst other things, depends on its insulation system. High voltage leads are a part of the insulation system and should be properly insulated. This includes positioning an insulation barrier between the leads and a tank on a certain distance. This distance affects the safety factors (breakdown probability) for such system. The paper presents optimization process with which both the breakdown probability and leads vs. tank distance could be minimized. It also proposes a method with which this optimization process could be confirmed.

Key words: power transformer, insulation, numerical calculation, optimization

1. INTRODUCTION

1.1. Electrodes in transformer

Power transformer with properly designed insulation is likely to be more reliable during its lifetime. One of the main tasks of insulation design process is to determine allowable distances between parts under voltage (electrodes). Electrodes of a transformer can be roughly divided into two groups: windings and leads. The purpose of leads is to form a conductive connection between transformers bushing (i.e. phase connector) and its associated winding.

1.2. Transformer leads

Transformer leads are made of copper wire, which varies by cross-section and paper thickness, depending on current density and voltage level, respectively. Low voltage (LV) leads represent no potential threat for insulation breakdown; however, more attention in design process must be given to high voltage (HV) leads, as their insulation must be properly chosen in order for partial discharge (PD) or oil breakdown not to occur.

1.3. Insulation of transformer leads

One of the measures for proper HV leads insulation, apart from paper thickness, is the setting of an insulation barrier between HV leads and transformer tank, as can be seen on typical transformer configuration on Figure 1, page 2.

1.4. Motivation

Main motive for conveying this resarch is to demonstrate how the barrier location, i.e. its horizontal distance from the leads and the tank, affects the insulation reliability of this system, and also how it influences the overall transformer dimensions.

This demonstration will be done according to the FEM numerical model and insulation will be designed according to “cumulative stress” method [1].

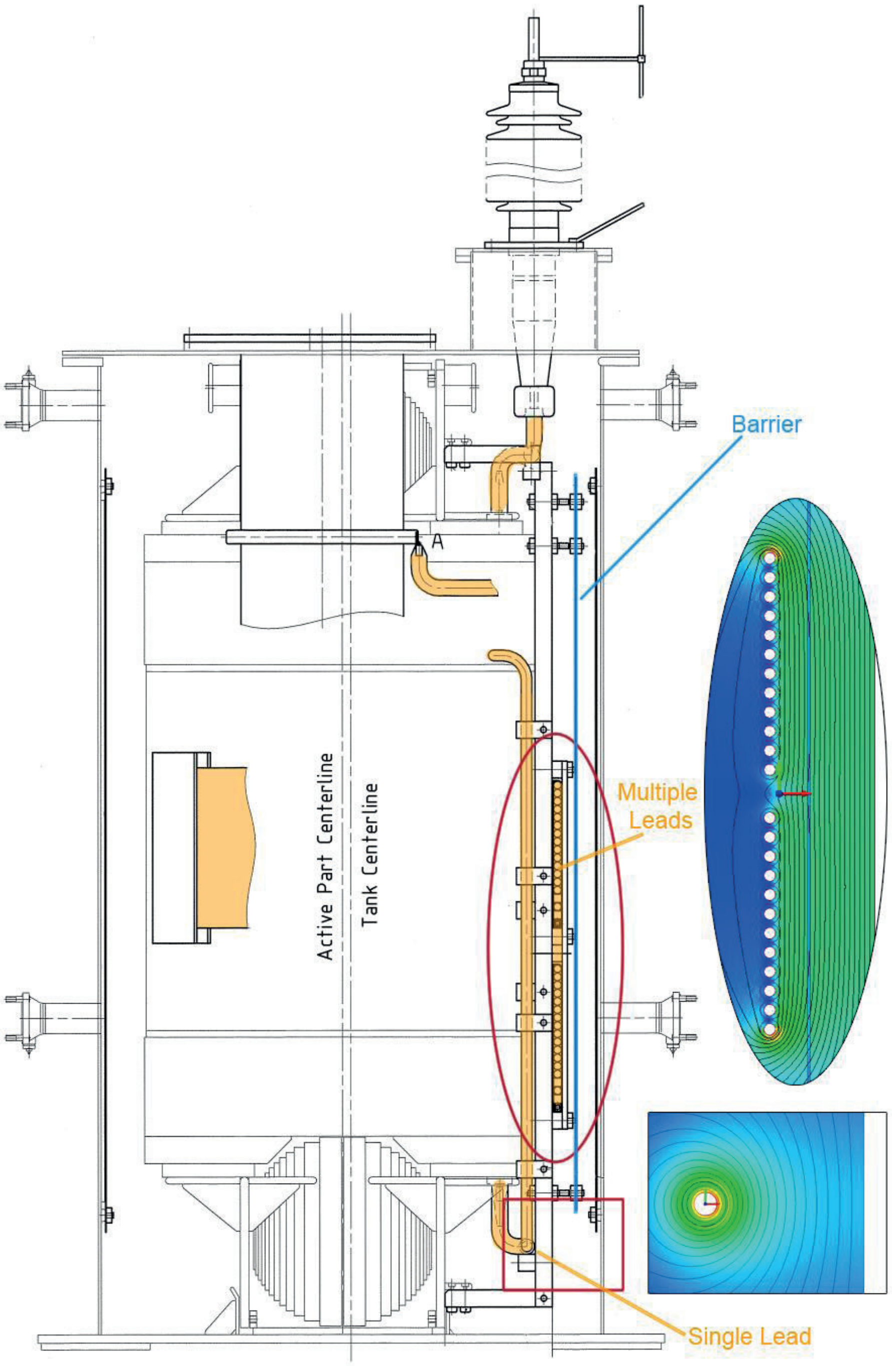

Figure 1 - Leads in transformer

2. INSULATION CALCULATION

2.1. Calculation of safety factors

According to cumulative stress method, probability of PD occurrence depends on average electric field along its streamline [2], with electrode voltage levels defined by international standard [3].

Safety factor σ of each streamline is calculated according to:

$$\sigma = \frac{E_{pd}(x)}{E_{av}(x)} \tag{1}$$

where E_{pd} is low probability PD/breakdown, and E_{av} is calculated according to Eq. (2):

$$E_{av}(x) = \frac{1}{x}\int_0^x E(x)dx \tag{2}$$

where:

$E(x)$ – electric field stress.

2.2. Optimization principles

Safety factors of each streamline are shown on Figure 2, separately for *left side of the barrier* (between leads and barrier) and *right side of the barrier* (between barrier and the tank). For this system to be optimized, two principles must be fulfilled:

a) safety factor values for left and right side streamlines must be greater than one

$$\sigma_L > 1$$
$$\sigma_R > 1 \tag{3}$$

b) minimum safety factor values for left and right side must be approximately equal

$$\sigma_L \approx \sigma_R \tag{4}$$

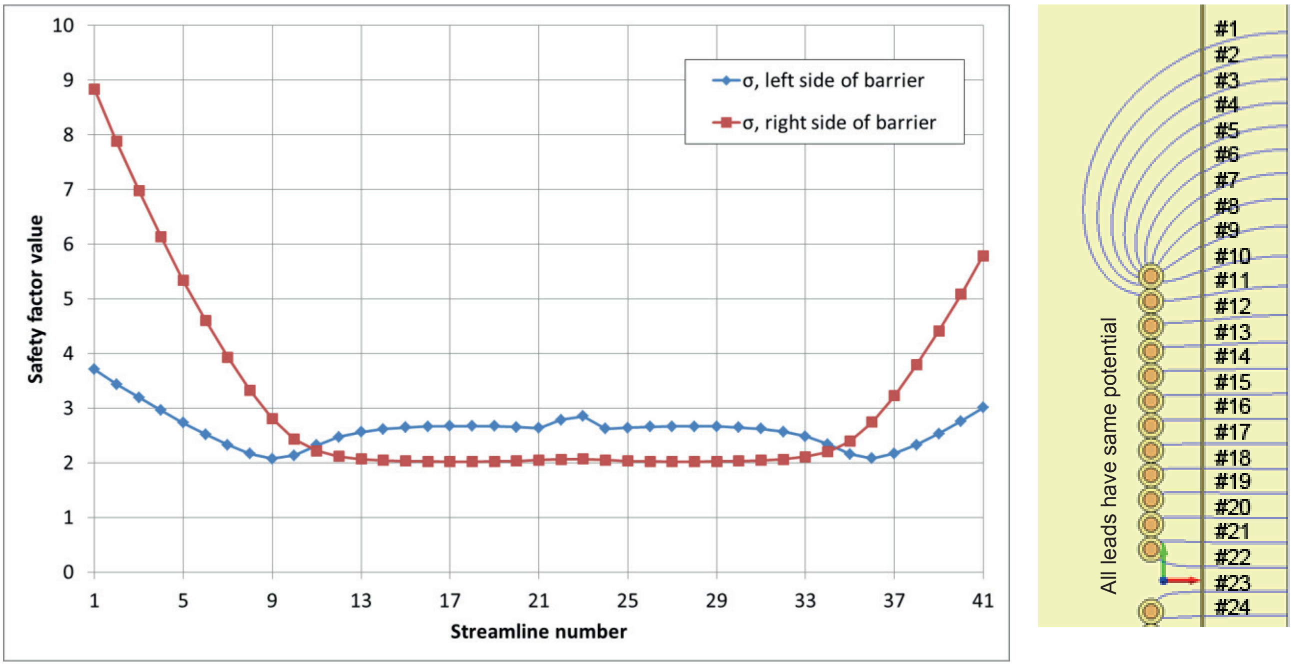

Figure 2 - Safety factors of streamlines on left and right side of the barrier

2.3. Optimization process

The optimization process consists of plotting safety factor values for different barrier distance, as shown on Figure 3.

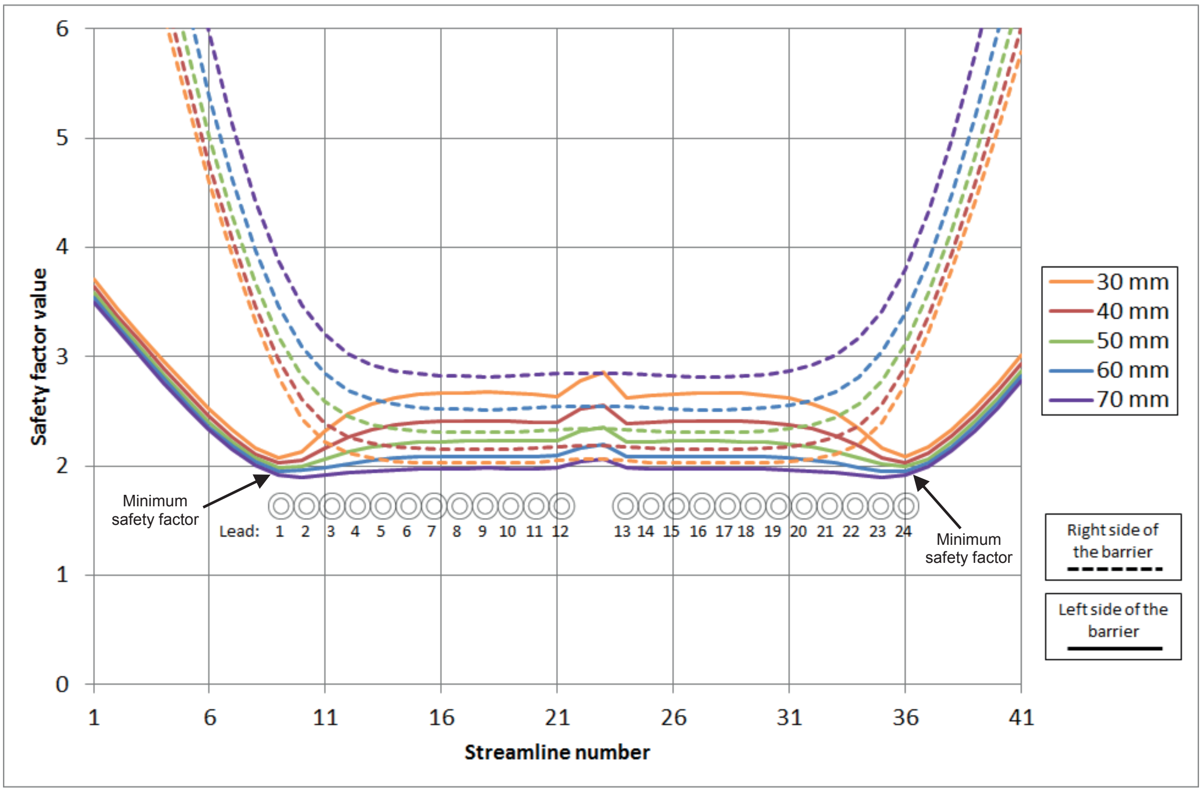

Figure 3 – Distance optimization according to principles a) and b)

From Figure 3, it can be seen that for the distance between barrier and leads of 50 mm (marked green), safety factors have approximately equal values in range of $2.2 \le \sigma \le 2.4$ for the leads in the center part of the bundle (for 7th to 19th lead, i.e. 16th to 31st streamline, green dashed line is equal to green continuous line), but they do not represent minimum values. In order to properly design the insulation, minimum safety factors should be observed, as they define weakest point in insulation [2].

These minimum safety factors (weakest points) are defined by 9th and 36th streamline, which occur on the first and the last lead of the bundle (where leads have the largest local electric field of 5.9 kV/mm in paper, Figure 4), but this is not always a case.

Figure 3 also shows that for the distance of around 30 mm (marked orange) these minimum safety factors of the *left* side of the barrier are equal to minimum safety factors on the *right* side of the barrier, with which principles a) and b) are both satisfied.

More detailed inspection of 30 mm barrier distance is shown on Figure 5.

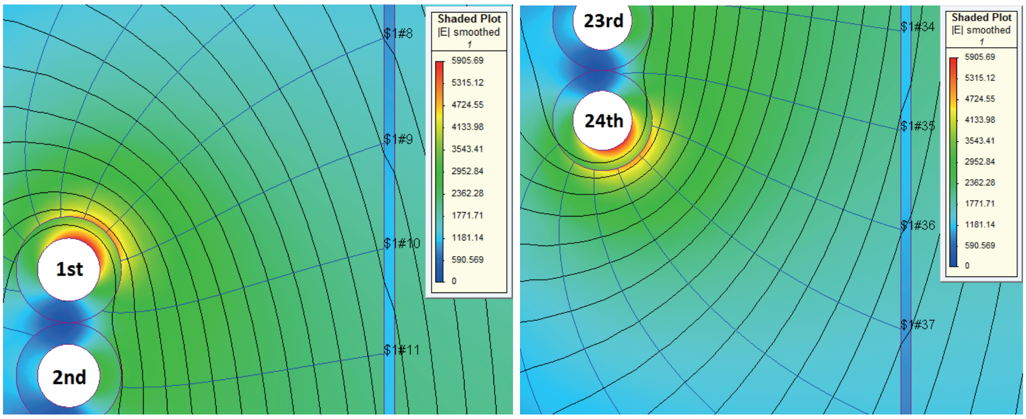

Figure 4 - Shaded electric field plot in V/mm, on first and last lead in bundle of 24 leads

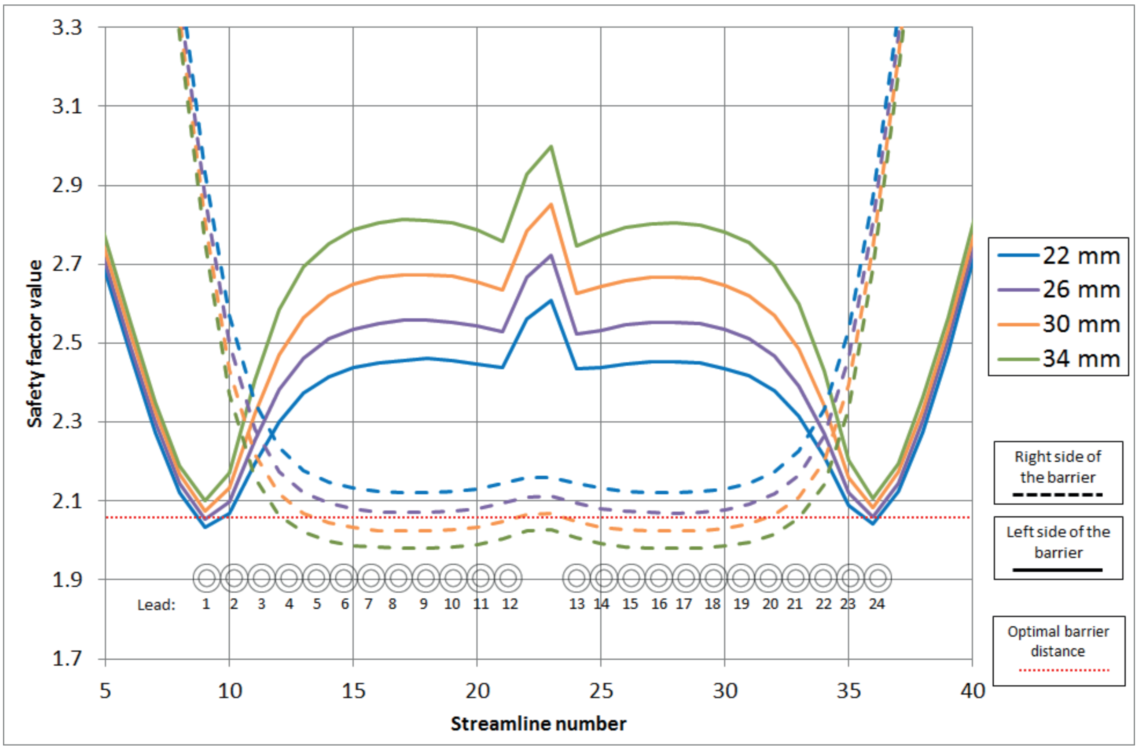

Figure 5 – Close-up of safety factor values in range of 22 mm and 34 mm barrier distance

Red dotted line on Figure 5 presents optimal safety factor which is reached for the barrier distance of 26 mm (marked purple). At this distance, both principle a) and b) is fulfilled with safety factor which is approximately $\sigma = 2.05$.

The reason that this value is optimal lies in the fact that whether the barrier moves left or right from current position, safety factor will be further decreased, i.e. there is greater probability that the oil breakdown will occur.

For example, if the barrier is moved closer to the leads (22 mm), safety factor *on the left side* of the barrier will be reduced to σ = 2.03 (part of the blue continuous line is beneath red dotted line), and if the barrier moves farther of the leads (30 mm), safety factor *on the right side* of the barrier will be reduced to σ = 2.02 (part of the orange dashed line is beneath red dotted line). Thus, the existing distance with σ = 2.05 is optimal.

3. CONFIRMATION METHOD PROPOSAL

In order to prove this concept of optimization, the following method is proposed:

a) an experimental model is simplified and it consists of a single lead and a barrier (as shown in Figure 6)
b) various distances between the lead and the barrier will be defined, upon which breakdown voltage will be measured
c) for this lead/barrier system, multiple set of voltage breakdown measurements will be performed

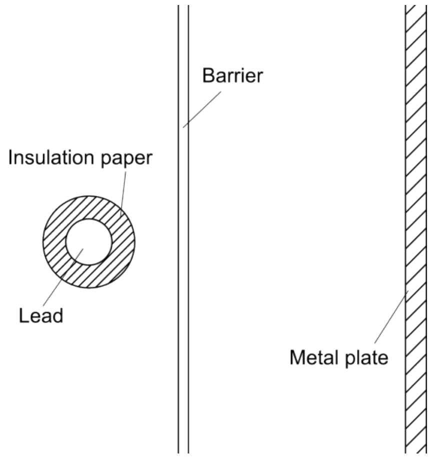

Figure 6 - Proposed method model

Three hypotheses which need to be accepted or rejected are defined as follows:

a) in the proposed experimental system of a lead and a barrier, an optimal barrier distance exists
b) the optimal barrier distance is based on safety factor calculation (“cumulative stress” method)
c) expected appearance of voltage breakdown curve is according to Figure 7

Following assumptions are taken into account:

a) the streamline with minimum safety factor is formed on the shortest path between the lead and the barrier
b) tolerances of the model are small enough not to affect the final result of the experiment
c) difference between optimum and minimum safety factor (marked with δ on Figure 7) is large enough to be statistically significant

For numerical part of the research, 2D FEM model will be used (Figure 8).

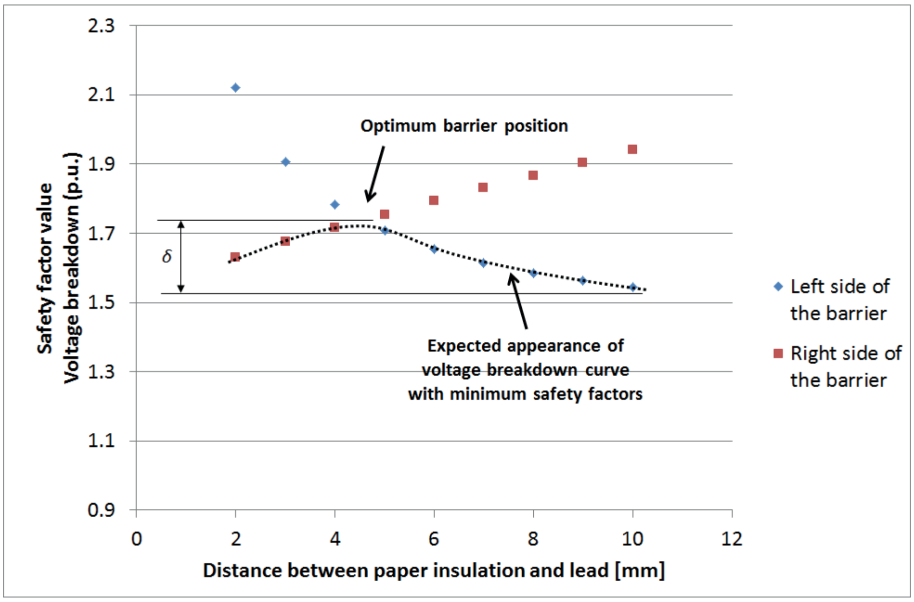

Figure 7 - Expected outcome of measured results

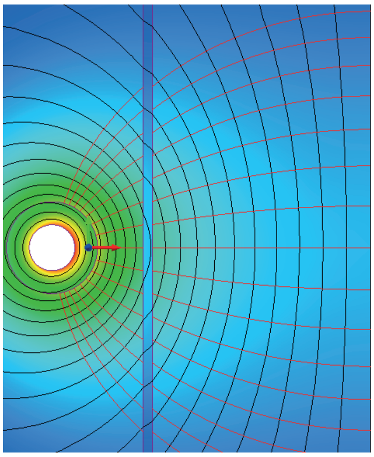

Figure 8 - FEM model for proposed research

4. LEAD OPTIMIZATION EFFECT TO TRANSFORMER WEIGHT

If the experimental part of the study confirms the proposed hypotheses, distance between HV leads and transformer tank could be reduced. This has two benefits

a) Total mass of a transformer could be reduced. This is shown on Figure 9 for a 40 MVA / 110 kV transformer
b) Overall transformer dimensions could be reduced. In situations with space limitations, this can be crucial factor in obtaining customers' tender

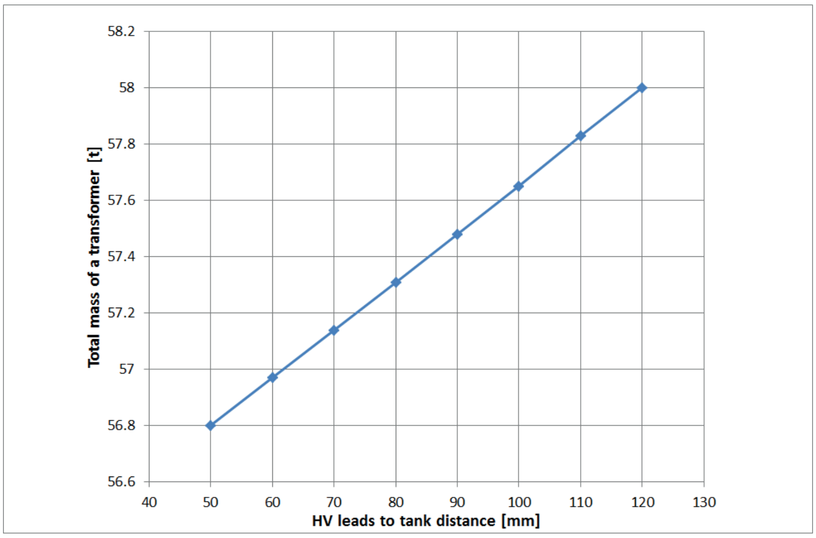

Figure 9 – “Total mass of a transformer” vs. “HV leads to tank distance” plot

5. CONCLUSION

The paper has presented how numerical calculation can be used for possible optimization of present transformer geometry. It has been shown that barrier position affects oil breakdown probability. Before taking any further steps in geometry alteration, this optimization concept has yet to be confirmed with a research which has also been presented. Depending on the results, transformer mass and dimensions could be altered, which would lead to production benefits and reduction of costs.

6. REFERENCES

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