Using the Electrical Field Analysis for Assessment of the Influence of Paper Insulation on Discharge Initiation in Oil

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Abstract: Conclusions about the influence of paper insulation on the electrical discharge initiation in mineral oil may be drawn mainly on the basis of experimental studies. However, in some cases, these conclusions may be supported by other methods like electrical field analysis using FEM. Determination of maximum values of electrical field stress in the vicinity of model electrode setups with paper insulation and without it, may be helpful in the deduction about the initiation mechanisms in paper-oil insulation setups. Obtained maximum values of electrical field stress (0.4 MV/cm for insulated HV electrode and 0.42 MV/cm for bare HV electrode), related to the measured in experimental works times to initiation, indicated that these mechanisms may be identical. It confirms the hypothesis that responsible for initiation processes weak points of paper-oil insulation setups, where oil has a technical purity, are included in oil, not in the surface of insulation wrapping or electrode metal.

Keywords: electrical field, paper-oil insulation, high voltage.

1. Introduction

The assessment of the influence of paper insulation on electrical discharge initiation in technical purity mineral oil has been considered for several years [1-4]. The main way to this assessment has been based on determination of the parameters describing the discharge initiation and propagation and on the observation of spatio-temporal development of discharges. Both the parameters like inception voltage, time to initiation or propagation velocity at inception voltage and spatio-temporal development of discharges require specially prepared laboratory systems where advanced electro-optical methods are used [2-6].

Authors' experimental studies were based on such prepared laboratory system and used approach relied on the comparison of some discharge parameters and observed phenomenon for two different kinds of electrode setups. First setup was a setup with insulated high voltage (HV) electrode and second with bare electrode having the same outer dimensions as the insulated. Simultaneously, the same field conditions were applied. It means that the same value of testing voltage was supplied (lightning impulse 1.2/50 μs of positive and negative polarity respectively) and the same quality mineral transformer oil was used in both cases [3, 4].

Mentioned investigations were performed in the fully automated laboratory system, based on the taking out the shadowgraph photos and on light emission registration. The shadowgraph photos were taken out using single-shot method where the YAG:Nd laser was used as a flash lamp. The light emission was however recorded on the basis of system with photomultiplier tube and digital storage oscilloscope [3, 4].

Because some conclusions noted on the basis of performed investigations, especially conclusion connecting times to initiation with well-known in oil insulation issues volume effect, were formed as the assumptions or hypothesis, the confirmation of such assumptions in the other type of researches seems to be important. One of such type of research method is the 3D simulation of electrical field distribution for the model paper-oil electrode setups used previously during experimental works Calculation of maximum values of electrical stress using finite element method, may successfully help in confirmation of wagered hypothesis. Thus, final comparison of the results from two independent research methods may give a base for much more sophisticated conclusions [7, 8].

2. Base for simulating works

2.1 Electrode models

As was mentioned above, two model electrode setups were used to the investigations. First setup was a setup with insulated HV electrode. This electrode was a brass wire having 4 mm in diameter. It was formed in the shape of capital letter U and after that coated with 5 mm wide and 0.1 mm thick crepe paper. Because few layers of paper were used, the final thickness of paper insulation on HV electrode was 0.4 mm. The grounded electrode in this setup was an aluminum plate having 195 mm in diameter. 5 mm in thickness insulating plate was deposited on it and 20 mm free oil space was then set. Second setup was a setup with bare HV electrode. HV electrode in this setup was also a brass wire. It was profiled to have the same outer geometric dimensions as the insulated HV electrode from first setup. Grounded electrode in second setup was identical as in the first. For these two types of electrode the wide research program was realized and its results were discussed in details in [4].

2.2 Times to initiation measured during experimental work

From the initiation of discharges point of view the most crucial parameter seems to be a time to initiation, especially when we compare the results of investigations made at the same field conditions between two considered electrode setups [4]. Time to initiation speaks however about the delay between the moment of supplying the voltage waveform to electrode setup and moment when discharge starts to develop. According to the physical theory, it is a time to initiation of discharge in weak points included in insulation setup. Weak points may be included both in the oil bath (gas bubbles, solid contaminations etc.), paper insulation (defects of paper structure) or on the surface of electrode metal (irregularities causing local increasing of electrical field). Obtaining the same values of times to initiation in two different insulation setups may indicate that the source of weak points responsible for discharge initiation is the same. Thus, it has to be oil bath, not the paper insulation or surface of metal. Such conclusion is probable because possibility that so physically different structures could be equally productive sources of initiation sites is hardly probable [3, 4, 7].

Equality of times to initiation was just obtained during authors' experimental works. Comparing the data for the appropriate voltage polarity, the lack of differences in the times to initiation of discharges developing in the considered model electrode setups at the same value of testing voltage is clearly visible. This equality concerns both the average values and standard deviations. The set of statistically estimated times to initiation was specified in Table I. The average values t_d and their confidence intervals and standard deviation for average values σ of log-normal distribution are included in this table [2, 4, 9].

Table 1. Experimentally measured times to initiation – parameters of log-normal distribution.

Voltage polarity	Positive (+)				Negative (-)			
Electrode type	Insulated		Bare		Insulated		Bare	
Testing Voltage	190 kV				192 kV			
Parameters [μs]	t_d **4.9**	σ **1.4**	t_d **5.0**	σ **1.3**	t_d **4.6**	σ **1.8**	t_d **4.7**	σ **1.4**
Confidence intervals [μs]	$4.4 < t_d < 5.6$	$0.8 < t_d < 2.3$	$4.2 < t_d < 6.2$	$0.3 < t_d < 2.9$	$3.8 < t_d < 5.5$	$0.9 < t_d < 3.1$	$3.7 < t_d < 6.2$	$0.2 < t_d < 3.5$

2.3 Hypothesis for simulating works

On the basis of experimental works one hypothesis was formed and this hypothesis became a source of approach for simulating works. It was related to the most stressed oil volume law; one of the fundamentals in the field of the setups with oil insulation. So, if the volume of oil being under electrical field higher than 90% of maximum value is similar in both considered cases (that is in setup with bare and insulated HV electrode), number of weak points contained in this volume, responsible for initiation processes, should be statistically the same too. Thus, if the calculated maximum values of electrical field stress, for the both electrode setups, will be close to each other, the similar should be the volume of the most stressed oil [7, 10].

Confirmation of such posed hypothesis may be reached through the simulating estimation of electrical field distribution and calculation of the maximum values of electrical field for both model electrode setups [7, 8].

3. Use of COMSOL Multiphysics

For electrical field distribution calculation in the considered model insulating setups the finite element method (FEM) applied in Comsol Multiphysics software was used [8]. As a well-known advanced mathematical method used in the electrical engineering issues for description of the problems of potential and electrical field distribution in the high voltage insulating systems and for analysis of magnetic phenomena occurring in the transformers, FEM seemed to be ideal for solution of stated problem [11, 12]. In considered case, empirical relationships from experimental studies could be confirmed by numerical calculations [7].

First step before starting the simulating works was a shaping of electrode setups in oil environment using 3D space. Modeled setups were identical with those used during experimental works. Because space shape of both electrode setups was the same, what was caused by identical outer dimensions of bare HV electrode with respect to the insulated one, only example for one of two setups was presented in Figure 1.

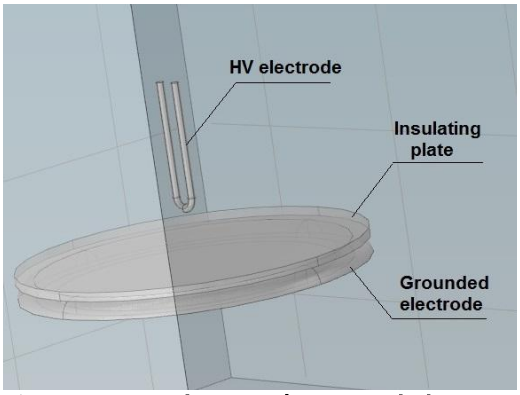

Figure 1. General view of setup with bare HV electrode modeled in Comsol.

Second step was an assignation of boundary conditions. From the point of view of electrical field analysis, important parameter of adopted materials was electrical permittivity. Materials were defined on the basis of COMSOL library and for oil was applied a value of 2.2 while for paper insulation on HV electrode and for transformerboard plate placed on the grounded electrode 4. Simultaneously, the electrical potentials corresponding with the values of testing voltage, at which the real measurements were realized, were defined. Adopted value for HV electrode was 190 kV while grounded electrode had assigned value 0.

Calculations were performed for both setups using high density mesh (extremely fine) in the space surrounded the HV electrode and low density mesh (extra coarse) assigned to the insulating plate. Interesting space was just a space in the vicinity of HV electrode because only in this space initiation of discharges may take place and maximum electrical field stress in this area is important.

Because the differences between both considered setups were very small (thin layer of paper insulation is very difficult to show), only results obtained for one of the setups were presented in Figure 2. There are the results for setup with bare HV electrode. In this Figure magnified fragments concerning the closest vicinity of HV electrode were quoted. For better visibility, the results were shown separately for x-y and y-z axis.

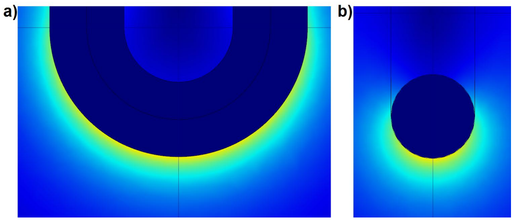

Figure 2. Electrical field distribution for setup with bare HV electrode: a) x-y axis, b) y-z axis.

4. Discussion

For both cases calculated values are close to each other. For setup with insulated HV electrode this value is 0.4 MV/cm while in the case of bare HV electrode 0.42 MV/cm. Such a small difference is a result of a very thin layer of crepe paper used as an insulation of HV electrode. It does not influence significantly on the field distribution, thus on the obtained maximum value of electrical field stress. From the other hand, noticed difference may result also from the existing boundary separating materials of different electrical permittivity (paper and oil). What is important to report, the values of maximum electrical field stress are in accordance with theory of electrical discharge initiation in mineral oil. Theoretical considerations indicated that the values of inception electrical field stress of slow discharges developing in mineral oil, in the setups of quasi-uniform electrical field distribution, are on the level from tenths of MV/cm to few MV/cm [2, 5, 6], thus exactly identical as the values obtained on the basis of presented simulating works.

Obtained similarities in the maximum values of electrical field stress in both considered electrode setups may suggest that in both cases the most stressed oil volume is also similar. Thus, since the most stressed oil volume is similar, the potential number of weak points included in this volume may also be, in both cases, the same. Very thin layer of crepe paper used as insulation covered the HV electrode is not affected so significantly on the electrical field distribution. So, the correlation between the measured, in the experimental research, times to initiation, and the obtained values of maximum electrical field stress, is an important factor confirming hypothesis on the important role of oil in the process of initiation of electrical discharges. The most stressed oil volume and weak points included in this volume may be successfully responsible for discharge initiation in the technical purity oil.

5. Conclusions

COMSOL Multyphysics software perfectly fulfilled its role in considered issues. Thanks to realized calculations confirmation of hypothesis from experimental works was obtained.

Support the laboratory studies by numerical calculations seems to be a good way to increase a value of performed scientific works. The drawn conclusions are stronger and more trustworthy.

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