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ACCURATE CALCULATION OF VERY HIGH DIVERGENT ELECTRIC FIELDS OF HIGH VOLTAGE SYSTEMS

الحساب الدقيق للمجالات الكهربيه شديدة التباعد بنظم الجهد العالى

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الخلاصة : حساب المجالات الكهربيه شديدة التباعد يلعب دورا هاما فى فهم عمليات الانهيار فى هندسة الجهد العالى . هذا الفهم لا بد منه من أجل تصميم أمثل لنظم العوازل الكهربيه . فى هذا الصدد يقدم هذا البحث اضافات جديدة على طريقة التمثيل بالشحنات الاصليه وذلك للتأكيد على دقة حساب المجال فى الاماكن الحرجة من نظم الالكترودات . بمراقبة زوايا شدة المجال الكهربى على سطح الموصل وكذا متابعة التكامل الخطى لشدة المجال الاقصى ، تم فى هذا البحث استعراض نتائج الحساب الدقيق لنظم الابرة واللوح الشائعه الاستعمال فى اختبارات التشجير لمواد البوليمر العازلة .
الطريقة المقدمه لا تعطى فقط دقة فى حسابات المجالات المتباعده لنظم الجهد العالى وانما تغنى ايضا عن أخطار استخدام الطرق التقريبيه الشائعه فى هذه الحسابات .

ABSTRACT - The calculation of very high divergent electric fields plays a dominant role for the full understanding of the breakdown mechanisms in the high voltage engineering. Approximate calculation methods may lead to a false dimensioning of the insulating systems. This paper introduces an accurate way for calculation such high divergent fields. Based on the optimized charge simulation method, the paper demonstrates an accurate field calculation of typical examples. The proposel examples are the shielded and unshielded needle-plate electrode systems used in the water treeling investigations of polymeric insulating.

1. INTRODUCTION

Very high divergent electric fields are suspected to play a dominant ...y most of insulation breakdowns, specially in vacuum and polymeric insulating ...ls [7-9]. This is a kind of insulation degradation, which leads by the time ...sulation breakdown.

To understand the water treeing behaviour in polymeric insulating ...erials, it has been necessary to simulate such high divergent fields in the ...oratory [7-9]. The well known needle-plate arrangement [9] is one of the typical ...rangements for investigation this phenomenon. However, such investigations ...are not capable to give a full unlestaning of the physical process, whether the electric field of such arrangements is not known at the needle tip or in the vicinity of it.

A closed solution to the needle-plate field problem can only exist, if the geometries of the needle are to be identified with a well known boundary problem in some coordinate system. This is not possible, since the used needles are of a long cylindrical shape and a very sharp end (mostly mass produced needles with scattering dimensions) [7]. Thus, it is difficult to identify such a problem with any known coordinate system. However, and because of the complexity of the problem, approximate methods for calculating such sharp needle point electric fields have been used to analyse experimental results and get ideas about the geometrical breakdown electric field strengths of such polymeric materials [7,8].

With the ever increasing progress in the numerical field calculation methods, it is now a main demand to find a more suitable method for an accurate evaluation of such electric fields.

Recently, effective and powerful program systems for the numerical calculation of electric fields have been developed [10-15]. From these methods, the charge simulation method (CSM) is one of the most widely used and powerful methods [10]. It has been recognized that the CSM is very competitive and often superior to the finite difference method (FDM), the finite element method (FEM) and the boundory element method (BEM), at least for treating two-or three dimensional fields within high voltage insulation systems, particularly where high accuracies within highly divergent field areas are demanded [14,15].

The CSM makes use of Mathematical linearity and derives Daplace's equation as a superposition of particular solutions due to discrete ficticious charges, which replace the physically distributed surface charges on the electrodes. The simulation accuracy depends strongly on the assumptions concerning the locations of the simulating charges. These assumptions are normally made on the basis of experience and may differ between various researchers [12]. As the electrode configuration increases in complexity, the experience of the researcher may fail to give the necessary assumptions. Thus, for a very high divergent electric field as that of a needle tip-plate, the optimized charge simulation method is one of the methods, which comes in question [11-13].

2. THE OPTIMIZED CHARGE SIMULATION METHOD

The method of optimized simulation systems is detailed in references [11-13]. The method is based on the application of optimization techniques for calculating the optimal amount and geometrical placement of the simulating charges to their respective contours, so that the error in the calculated boundary potential is minimized. By this means, the use of a few number of simulating charges leads to an accurate simulation of the electric field, independent of experience.

A practical application of this method can be achieved, if the evaluation of the optimized charge simulating systems is limited on the high stressed zones only, while the less stressed zones may be simulated in the conventional way. Such a procedure is possible according to the fact that the charge simulation method is based on the superposition of particular solutions [10].
In the next following text a short notation on the procedure is described; for details it is reffered to [11-13].

The electrode system will be devided into high stressed regions and less stressed regions. The less stressed regions will be conventionally simulated. The high stressed regiones will be presented by a sufficient number of interval points and will be simulated by means of a charge simulating system ($\underline{Q}$) having any arbitrary initial amounts. The locations and amounts of this charge simulation system will be iteratively corrected by means of minimization algorithms, so

that the potential error F along the simulated contour ℓ becomes minimum according to the following equation,

$$F=\frac{1}{\ell}\int_{\ell}(\phi_a-\phi_r)^2 d\ell \quad ...(1)$$

Thereby corresponds ϕ_a to the potentials along the simulated contour due to the excitation of the charge simulating system and ϕ_r is the rated boundary potential. The minimization of the above error function F corresponding to a system of $\tilde{n}$ simulating charges can only be realized by means of varying the geometrical placements $r_1, \ldots, r_{\tilde{n}}$ and the amounts $Q_1, \ldots, Q_{\tilde{n}}$ of the charges. These represent the independent variables of the function F, which can be rewritten as:

$$F= f[(X)] \quad = , \qquad (X) = (r_1, r_2, \ldots, r_{\tilde{n}}, Q_1, \ldots, Q_{\tilde{n}}) \quad ... (2)$$

The resulting charge simulating system after minimizing the error function F is the so-called optimized charge simulating system.

To satisfy the boundary conditions in the less stressed zones, which are conventionally simulated, the conventional charge simulating system must be recalculated after every iteration [13], so that the equipotential surface intersects the contour points. This demand is represented by the following system of equations, which must be solved for the unknown amounts of the conventional charge system (Q).

$$(P).(Q) + (\tilde{P}).(\tilde{Q}) = (\phi) \quad ...(3)$$

Hereby, $(\tilde{P})$ is the potential coefficient matrix of the optimized simulating charge system $(\tilde{Q})$ with respect to the contour points of the less stressed zone, (P) is the matrix of the potential coefficients of the conventional charge system (Q) with respect to the same contour points and (ϕ) is the column of the boundary conditions to be satisfied in the contour points.
The product $(\tilde{P}) . (\tilde{Q})$ gives the potential portion (ϕ_0) caused by the optimized charge simulating system at the contour points.

$$\text{With } (\tilde{P}) . (\tilde{Q}) = (\phi_0) \quad ... (4)$$

equation (3) can be rewritten as :

$$(P) . (Q) = (\phi) - (\phi_0) \quad ... (5)$$

This system of equations should be solved for the unknown charges (Q). It is apparent, that the system matrix (P) should only be once built and inversed for the whole calculation run, because the necessary variation in the optimized charge simulating system goes only as a modification of the potential boundary condition in the calculation.
When the potential error along the high stressed simulated contour ℓ reaches an acceptable pregiven potential error value, the calculation procedure is terminated.

3. NEW ADDITIONAL CONSTRAINS FOR GAINING HIGHER ELECTIC FIELD ACCURACY

The special geometrical properties of the needle-plate problem must be considered. For gaining a highst possible simulation accuracy, some additional constrains are introduced in this paper.

First of all, a concentration of simulating charges should be undertaken in the region of the needle tip and its surrounding. However, since the potential

error to be minimized, eqn. 1, is the error along the whole critical contour, some constrains must be done to insure no accumulation of potential errors at the needle tip and its neighbourhood For this extend, the following two restrictions have been found to be efficient for controlling the accuracy of the calculated eletric field values of the critical regions.

3.1. Controlling An Electric Field Angle Error Function

In addition to the potential error function given by eqn. 1, an electric field angle error function F_θ is introduced, where

$$F_\theta = \frac{1}{\ell} \int_\ell (\theta_a - \theta_r)^2 d\ell \quad \ldots (6)$$

Thereby, θ_a is the electric field angle along the simulated critical contour due to the excitation of the charge simulating systems and θ_r is the rated boundary field angles at the interval points; "the electric field should be perpendicular to the equipotential surface of the forgiven contour of the electrode".
Thus, the iteration process is not allowed to stop, before F_θ is equal or less than a forgiven angle error tolerance "in the range of 0.0001 square radians .

3.2. Controlling The Electric Field Line Integral Along The Critical Breakdown Path

As a second constrain, the electric field line integral along the shortest path between needle tip and the opposed plate has been always compared with the potential difference between both electrodes.
In case of accurate simulation of tip electric field, the line integral of the electric field will be equal to the potential difference U between both electrodes verifying the following equation,

$$\int_1^2 \vec{E} \cdot d\vec{x} = U \quad \ldots (7)$$

where $\vec{E}$ is the electric field intensity, $\vec{x}$ is the critical path of integration, the point 1 corresponds to the needle tip and point 2 corresponds to the plate.

4. EXECUTIVE EXAMPLE

The simulation results of two typical needle-plate problems are introduced in this paper. Fig. 1.a. illustrates the unshielded neede - plate configuration and Fig. 1.b. illustrates another arrangement with a guard ring. The dimensions of the arrangements have been chosen in agreement with the treeing needle - plate arrangements used in laboratory experimental investigations [7-9].

With a needle shaft diameter of 1 mm, needle tip angle of 30° and a needle tip curvature radius of 3 μm, the electric field intensity has been calculated for a potential difference of 100 kV between needle and plate. For comparative purpose, the field calculation of both arrangements has been done for a tip-plate distance of 4 mm; (s = 4 mm in configuration 1.a and insulation thickness d = 6 mm and needle penetration depth e = 2 mm fur arrangement 1.b).

Because of the rotationaly symmetrical nature of the electrode configurations, point - and ring charges has been used in the simulation process. Thereby, a needle tip penetration depth of 15 μm has been taken as the critical zone of the needle. For this region, an optimized charge simulating system of 4 Point

charges and 3 ring charges is considered. Thereby, a concentration of the charge locations has been undertaken in the region of tip curvature to insure an accurate simulation of the tip. The so called non-critical regions of the arrangements are simulated by means of a conventional charge simulating system consisting of 15 point charges for the rest of needle shaft, 7 ring charges for the plate opposite to the needle and 7 ring changes for the guard ring of configuration 1.b.

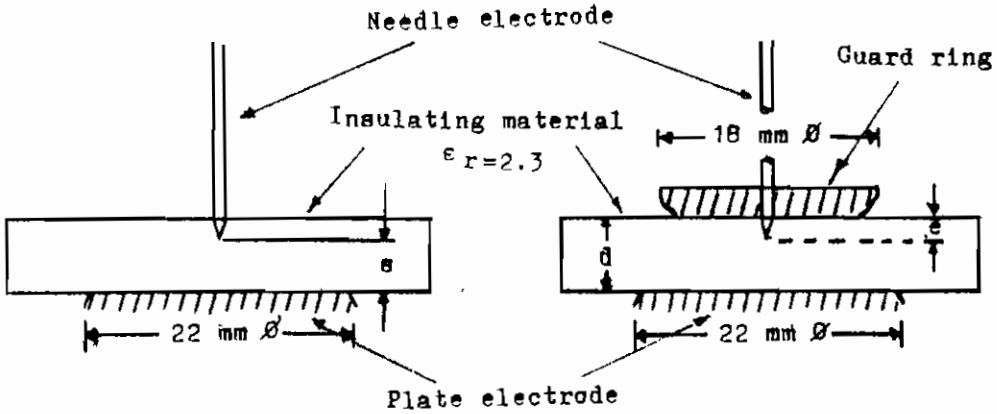

Fig.1.A. Fig.1.B.

Fig.1. Typical needle - plate arrangments (dimensions as in text)
"1.A." Unshielded arrangement (s = distance between needle tip and plate).
"1.B." Shielded arrangement (d = insulation thickness and e = needle depth penetration)

Fig.2 illustrates the courses of the electric field intensities, corresponding to diffenent values of the vertical axis r, against the horizontal breakdown paths x for the needle-plate configuration of Fig.1.a. The use of logarithmic paper is necessary in this problem, because of the large distances of the breakdown paths compared with the needle dimensions.

Fig 3 illustrates the courses of the electric field intensities in the same manner as in Fig. 2, but for the needle-plate arrangement with guard ring shielded electrode system.

The illustrated dashed lines in the first 1 μm distance in both figures 2 and 3 indicate linearly falling electric field values in this very critical zone (in the logarithmic scale). It is also seen from both figures, that the critical field intensity is that of the needle tip (r=0).

The guard ring presence is found to strongly reduce the maximum electric field intensity (nearly to the half value). The field course against the breakdown path distance x is, however, of the same shape for both cases with or without guard ring.

It should be mentioned here, that the mostly used hyperboloid approximation formula for the needle-plate arrangement [7,8] can not be used to solve the needle-plate problem with guard ring. Moreover, compared with the accurate solution introduced in this paper, this formula causes an error of (-12%) in the maximum field intensity value for the configuration without guard ring.

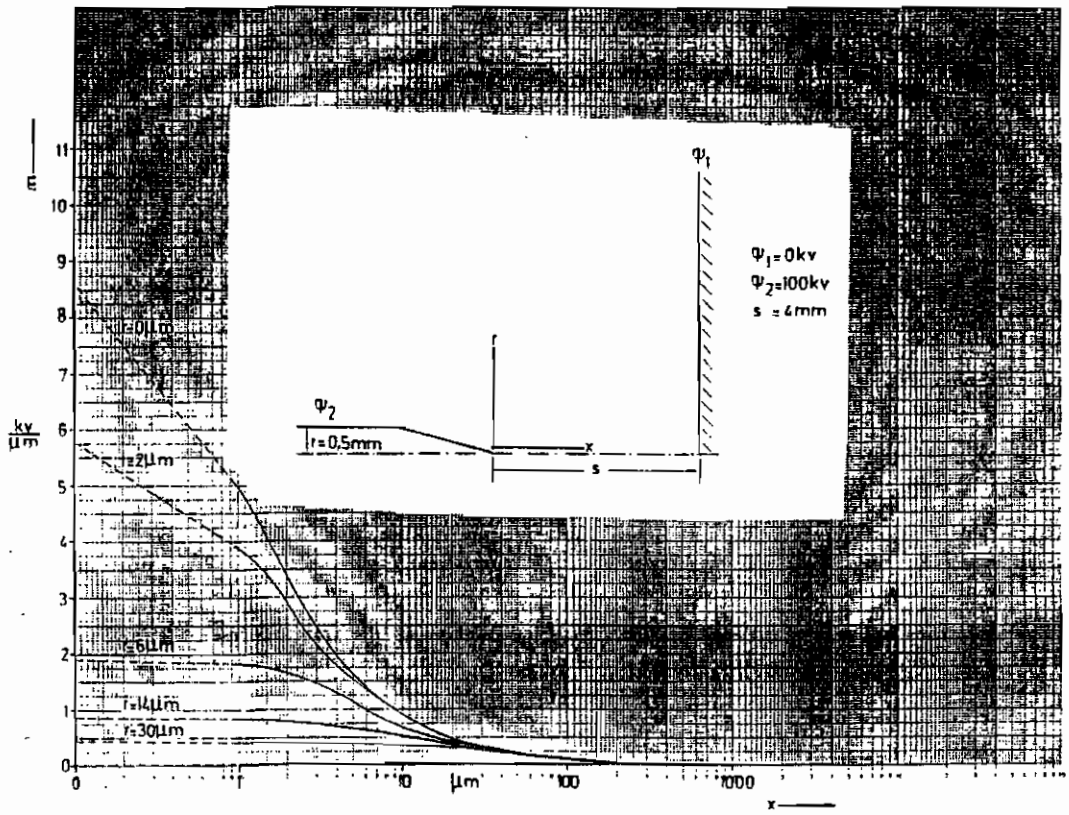

Fig.2. Courses of electric field intensities E against horizontal breakdown paths x for different vertical values of r, corresponding to unshielded problem as in Fig.1.A.

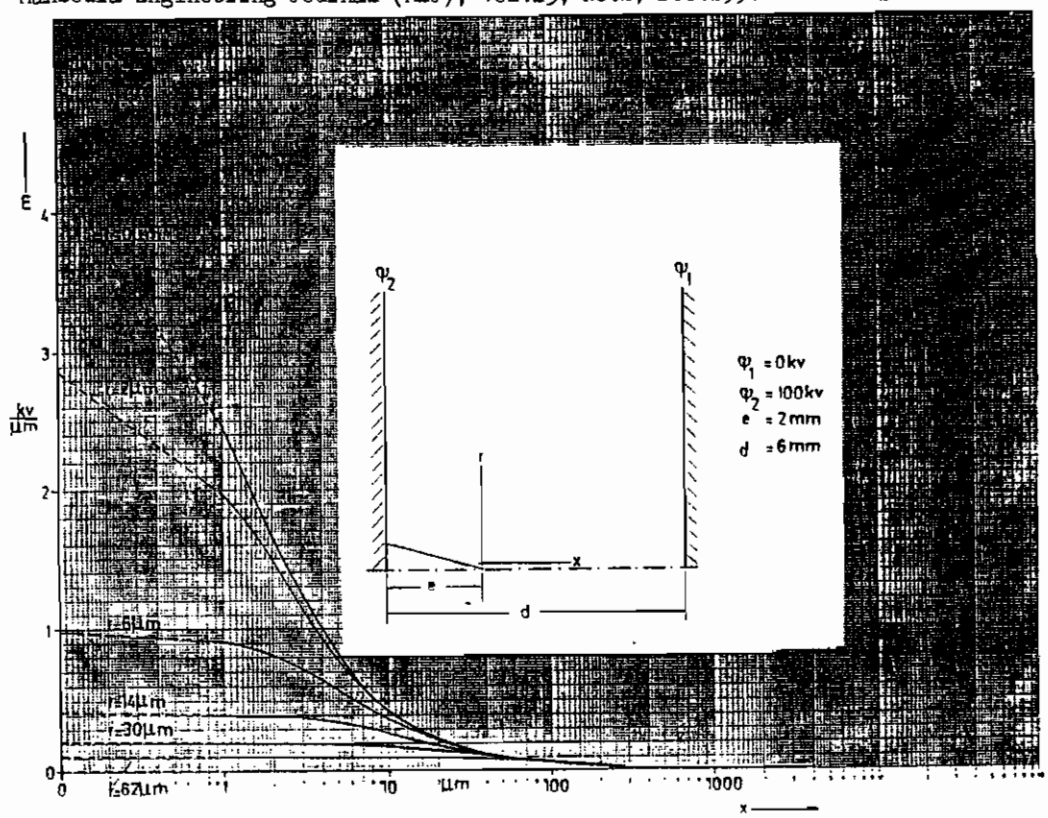

Fig.3. Courses of electric field intensities E as in Fig.2, but for shielded arrangement in Fig.1.B.

5. CONCLUSIONS

The paper introduces simple controlling constrains for insuring an accurate simulation of the very high divergent fields of high voltage systems. Based on the optimized charge simulation method, the accurate calculation of a typical needle - plate arrangement showed the great influence of shielding. A guard ring presence caused a reduction of the maximum field strength value of the needle - plate arrangement of about 50% of its original value. The introduced method does not only overcome the errors associated with approximate field calculation methods, but also enables an accurate simulation of complex arrangements, which can not be approximated.

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