Thoughts on the Possibility of Damage of High-Voltage Electrical Insulation below the So-Called Inception Voltage: A Proposed Solution and Some Further Comments – Part II

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Abstract

An interesting event reported long time ago, namely that charging phenomena may happen below inception voltage, is further discussed in the present paper. A previous paper in this journal referred to the historical background of the research on this phenomenon and also to the relevant equations governing it. As was pointed out, differential equations are used in order to correctly approach the charging events below inception voltage.

In the present paper, an iterative method and the finite element method are used to establish an algorithm with two loops. A typical case is studied, where a solid sheet insulation contains a void. The inception voltage is calculated by the proposed algorithm under the typical case for both AC and DC voltage.

Keywords

Partial discharges, charging phenomena below inception voltage, high voltage insulation, cavities, inception voltage, simulation

Introduction

In electrical engineering, partial discharge (PD) is a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors. PD can occur in a gaseous, liquid or solid insulating medium. It often starts within gas voids, such as voids, for example, in solid epoxy insulation or bubbles in transformer oil. Protracted partial discharge can erode solid insulation and eventually lead to breakdown of insulation [1].

Discharge inception voltage (DIV) is such a voltage, above which, partial discharge (PD) occurs. When measuring DIV by experiments, a PD detection system is used. As the voltage applied on the insulating samples increases, PD detection begins to register PD signals, and that is the so-called DIV.

Then the question comes whether the so-called DIV is the real DIV. Due to background interference or the limitation of equipment sensitivity, it is possible that PD happens below the so-called IV and the detection equipment cannot detect or recognize these PD signals. To put it another way, there may be charging phenomena that can go undetected by a PD detection system. In other words, it is difficult to ensure that there is no PD (or charging phenomena) below the so-called DIV. Detection of PD or not depends on the sensitivity of the PD detection system. Under these circumstances, PD (or charging phenomena) may happen and the insulations may be damaged to some extent, when they are below the so-called DIV. Sudden insulation damages have been reported in [2]. In [2] was also reported that sub-corona current in a polymer cavity with an applied voltage below DIV can cause cavity surface chemical changes that are similar to changes that occur when polymer insulation fails under full corona. Furthermore, a previous publication in this journal [3], proposed an approach to the subject of charging phenomena below inception voltage which is to calculate DIV by solving differential equations.

When investigating the discharge mechanism in insulation with voids, many researchers have a similar approach. The cavity will discharge when the voltage across the cavity attains its breakdown value [4]. Based on such mechanism, many researchers calculate the DIV. Expressions are derived for the discharge inception voltage, at which discharges occur in enclosed voids within the insulation of single-core [5] and three-core [6] cables. In reference [7], researchers report a technique for estimating the DIV in case of discharges occurring in voids in solid sheet insulation in the ambient medium of air.

However, these approaches present two problems. One is the necessary of analytical solution. The details of voids and defects are ignored to a certain extent, thus the equations are solved in an analytical way. When there is no analytical solution, these approaches fail. The other one is that the material parameters must be linear. In cross-linked polyethylene (XLPE), for example, such conditions are usually not met. To overcome these two problems, in this paper, iterative method and finite element method (FEM) are used to establish an algorithm with two loops. A typical case is studied, where a solid sheet insulation contains a void. The DIV is calculated by the proposed algorithm under the typical case in both AC and DC voltage.

Algorithms

1. Outer Loop

Partial discharges within a solid insulating material are usually initiated within gas-filled voids. If the voltage stress across the void is increased above the strength of the gas within the void, PD activity will start within the void. For insulating samples with voids, DIV is such a voltage, at which, the maximum electric field in voids equals the local breakdown field strength.

When details of voids and nonlinearity of material parameters are considered, there is no analytical solution. As a result, it is difficult to calculate voltage from electric field directly. In this case, the procedure may be as follows.

First, lets consider a problem in Fig. 1(a) with analytical solution, and a similar problem in Fig. 1(b) without analytical solution.

Problem (a) is a plate capacitor, the electric field intensity $E = U/L$. This means we can calculate electric field by voltage. Also, we can have $U = E*L$. That means, that it is possible to calculate voltage from the electric field. Problem (b) presents a similar problem, but without analytical solution. This means we cannot have an expression to describe the relation between E and U directly. In the present paper, it is obvious that the problem is also without analytical solution.

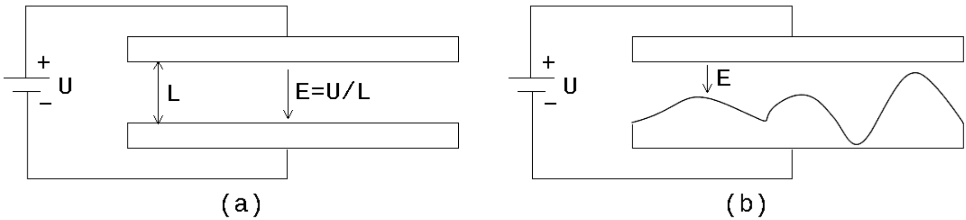

Fig. 1: (a) Geometry that can be approached by analytical solution, (b) Geometry that cannot have an analytical solution

To solve such a problem, FEM is a common method. In mathematics, FEM can solve partial differential equations under boundary conditions. Volt-age is a kind of boundary condition. That means if the voltage is given, the boundary conditions are known and the FEM problem can be solved. So, when we use FEM, the electric field may be calculated from the given voltage.

In conclusion, one may say that by numerical calculation of electromagnetic fields, when the voltage is viewed as a kind of boundary condition, it is possible to calculate the electric field from the voltage. We can select voltage and calculate field by this voltage. If the field calculated equals to the local breakdown field strength, the voltage assumed is the solution. Thus, an iterative method is suggested, where by continuous trials and adjustments a solution can be found.

Consequently the steps followed are given below:

Step 1: Guess a voltage and apply it on the insulating sample.

Step 2: Calculate the electric field from voltage (discussed later in the inner loop). Subsequently, we have the maximum electric field in voids under this voltage.

Step 3: If the maximum electric field equals the breakdown field strength, this is the DIV we want. If not, guess another voltage, and go back to step 2.

This procedure is a loop, and the computational efficiency is influenced by the way we guess voltage in step 3. It is clear that the voltage and the electric field are positively correlated. In other words, the electric field increases when the voltage is higher. That gives a consistent principle that if we want to have a higher electric field in step 2, we must guess a higher voltage in step 3, and vice versa. By this principle, we may solve the outer loop fast.

2. Inner Loop

Having in mind the nonlinearity of material parameters, the equations used are as

$$E = -\nabla V \quad (1)$$

$$J = \begin{cases} sE & \text{DC} \\ (s + \mathrm{j}\,\omega\varepsilon)E & \text{AC} \end{cases} \quad (2)$$

$$\nabla \cdot J = 0 \quad (3)$$

where, E is the electric field intensity, V is the voltage, s is the electrical conductivity, ω is the angular frequency of the voltage applied, ε is the dielectric constant, J is the electric current density, j is the imaginary unit. In the AC case, the angular frequency is set here as 100π rad/s.

Eq. (1) is the definition of voltage. Eq. (2) is the constitutive equation, which describes the relation between the current and the electric field. Eq. (3) is the current conservation equation. When we substitute Eqs. (1) and (2) into Eq. (3), we will have Bruning's quasi-steady equation for current flow, which has been discussed in our previous publication in this journal [3].

In Eq. (2), the electrical conductivity s is influenced by the electric field intensity E, as Eq. (4) shows

$$s = s(E) \quad (4)$$

Although conductivity depends on both temperature and electric field according to [10], in the present case temperature does not change and the conductivity is determined by the electric field. Consequently, eq. (4) is used. Such phenomena have been reported and measured in [8] in XLPE. High field conductivity is a nonlinear variable under different electric fields. That causes the difficulty when we use traditional FEM to solve these equations.

Consequently an iterative method is used whose procedure is as follows:

Step 1: Guess a voltage distribution.

Step 2: Calculate material parameters by equation (4) based on the voltage distribution.

Step 3: Treat material parameters as constants and solve equations (1) to (3) by traditional FEM (discussed later). Thus we have a new voltage distribution.

Step 4: Compare the new voltage distribution solved and the previous one. If they are almost the same, it is the solution we want. If not, delete the previous voltage distribution, adopt the new one, and go back to step 2.

This procedure is also a loop, but we only need one guess in step 1, and the rest of the loop is almost without human intervention. So the computational efficiency is almost determined by the equation itself. In other words, the degree of nonlinearity in equation (4) is the main factor.

Traditional FEM

In mathematics, FEM is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function [9], [10].

When we treat material parameters as constants, Eqs. (1) to (3) make up a traditional FEM problem, and many software programs can solve such a problem. Usually, besides the equations, a traditional FEM problem contains other three parts, namely geometry, materials and boundary conditions. Geometry defines the domain. Materials define the parameters used in the constitutive equation in each domain. Boundary conditions define the constraint conditions on the boundaries.

1. Geometry

A typical sample used in PD experiments is a solid sheet insulation that contains a void. Lets assume that the insulation is a cylinder. Its top surface is in contact with the high voltage electrode, while its bottom surface is in contact with the ground electrode. The void is a spheroid in the center of the sheet, as shown in Fig. 2. In typical size, the sheet diameter is $2R = 20$ mm and the height is $H = 10$ mm. The void width is $2a = 12$ mm and the depth is $2b = 6$ mm.

The problem of the void in the present paper can be treated as a two-dimensional one. A cylindrical coordinate (x-axis and y-axis are shown in the figure) is enough, thus reducing calculation complexity.

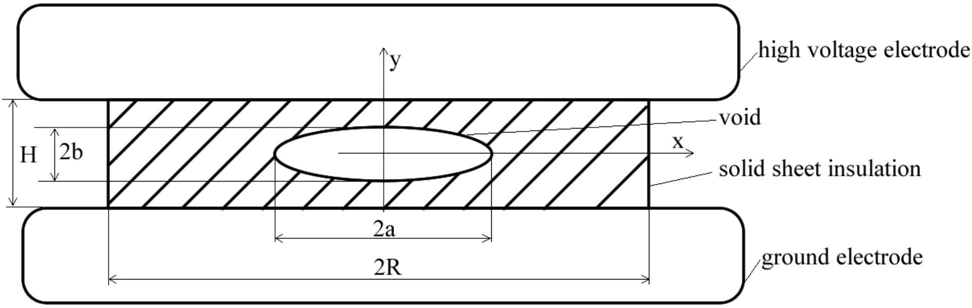

Fig. 2: Cross section of insulation with a void

Tab. 1: Material Parameters

Material	Conductivity (S/m)	Dielectric constant	Breakdown field (V/m)
Insulation	$3.8\text{x}10^{-16} \sim 3.8\text{x}10^{-14}$*	2.3 ε_0**	$120\text{x}10^{6}$
Void	$5\text{x}10^{-14}$	ε_0	$3\text{x}10^{6}$

* Conductivity is influenced by field. High field conduction measurements are given in reference [7].
** ε_0 is permittivity of vacuum.

2. Materials

To describe an insulating material in this case, three parameters are needed, namely conductivity, dielectric constant and breakdown field strength. Their values are listed in Tab. 1. The conductivity of insulation is calculated by Eq. (4) based on the voltage distribution in the inner loop, and is treated as a constant during FEM procedure.

It should be pointed out that these parameters are influenced by temperature. Void material parameters are also influenced by pressure. Dissociation and other chemical changes make the problem more complex. That means all these parameters should be treated as nonlinear variables as the conductivity of insulation [11], [12]. However, in the present paper, in order to simplify, these parameters are selected under standard atmospheric pressure and indoor temperature, and are treated as constants.

3. Boundary Conditions

In mathematics, in the field of differential equations, a boundary value problem is a differential equation together with a set of additional constraints, called the boundary conditions. In this case, there are two Dirichlet boundary conditions. One is that the top surface of insulating sample is in high voltage, which is guessed in the outer loop. The other is that the bottom surface is in ground voltage.

Solving

The present work studies, a typical case, where a solid insulation sheet contains a void. In order to find a solution for the inception voltage, the two loops of the algorithms described above must be applied. The outer loop determines the DIV, while the inner loop computes the electric field from the voltage. The main step of the inner loop is to solve a traditional FEM problem, which contains equations, geometry, materials and boundary conditions.

All these algorithms are programed in COMSOL Multiphysics, which is a finite element analysis solver and simulation software for various physics and engineering applications, especially coupled phenomena, or multiphysics.

Results

1. DIV in AC Case

DIV in AC case is 23×10^3 V, and the electric field distribution under DIV is shown in Fig. 3. In (a), the electric field in the void is higher than that in the insulation. In (b), it is clear that the maximum field appears in the major axis of the ellipsoidal void. This suggests PD are likely to happen in these parts. More decomposition product will be detected there.

2. DIV in DC Case

DIV in the DC case is 160×10^3 V, and the electric field distribution under DIV is shown in Fig. 4. In (a), the electric field in the void is lower than that in the insulation. In (b), it is clear that the maximum field appears across the minor axis of the ellipsoidal void. This suggests PD are likely to happen in these parts. More decomposition product will be detected there.

3. Comparisons and Discussions

DIV in AC and DC cases are very different mainly in two parts.

(1) DIV in DC case is much higher than that in AC case. This suggests that it needs a much higher source in DC PD experiments.

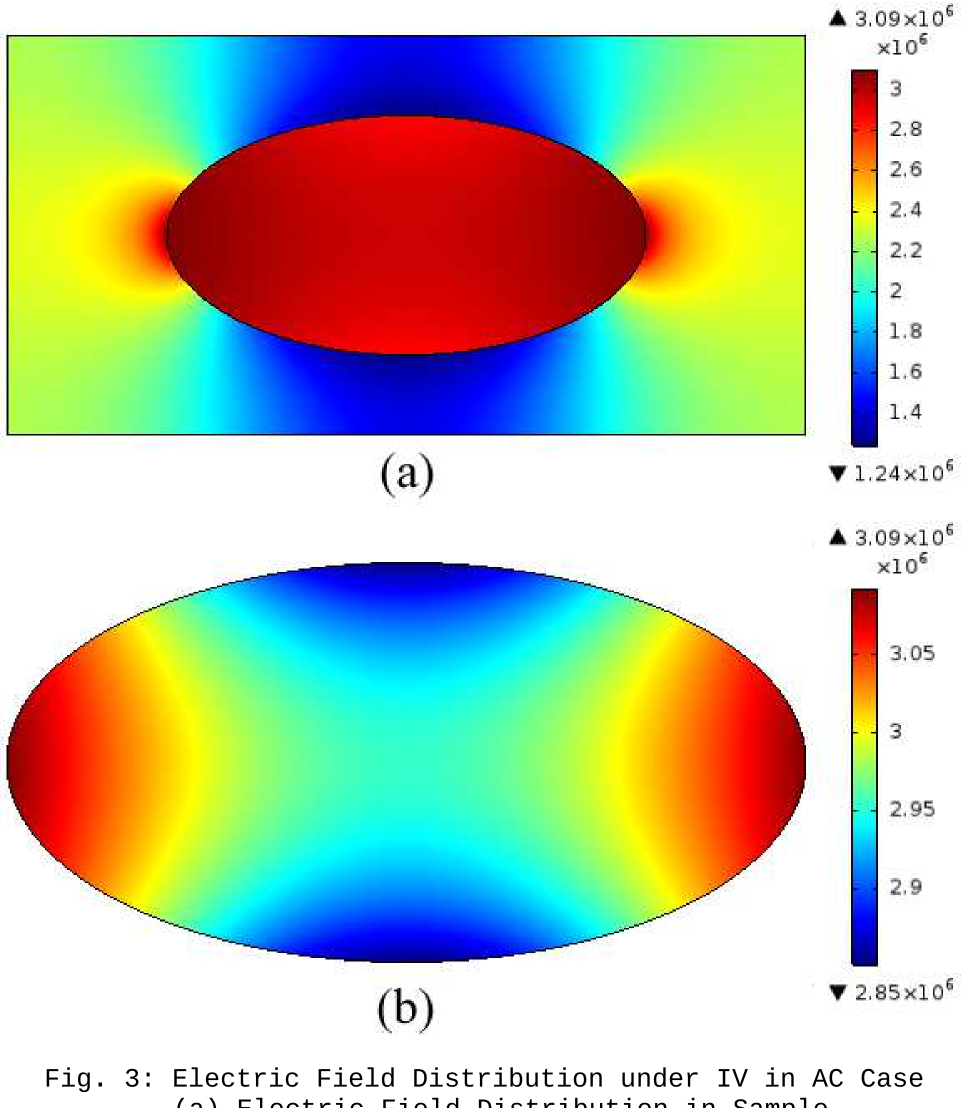

Fig. 3: Electric Field Distribution under IV in AC Case
(a) Electric Field Distribution in Sample
(b) Electric Field Distribution in Void

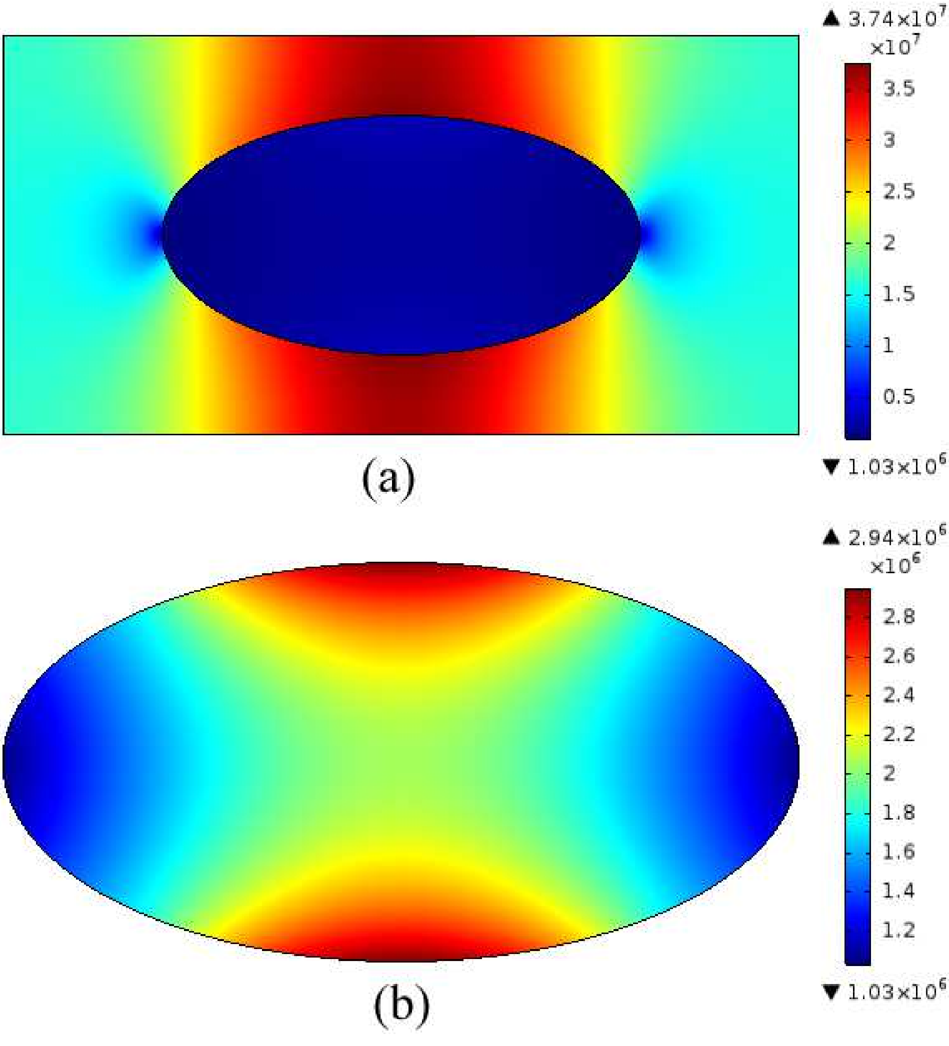

Fig. 4: Electric Field Distribution under IV in DC Case
(a) Electric Field Distribution in Sample
(b) Electric Field Distribution in Void

DIV in the AC case is 23×10^3 V whereas the DIV in the DC case is 160×10^3 V. In other words, to observe PD under DC conditions in the same insulation sample, a higher source is needed,

(2) PD happens in totally different parts of the void. PD under AC conditions are likely to happen in the major axis of the ellipsoidal void, whereas PD under DC conditions are likely to happen in the minor axis.

To sum up, when comparing Fig. 3 and Fig. 4, a lower AC voltage can start PD whereas a much higher DC voltage is needed when a DC voltage is applied. Furthermore, the location where PD occurs is different in the two cases.

Theoretically, the DIV calculated in this paper is the real DIV other than the so-called DIV measured by experiments. It is speculated that the real DIV calculated here is lower than the so-called DIV. When the insulating sample is under a voltage between the real DIV and the so-called DIV, PD happens (or at least a charging phenomenon), but the charging amount is not very much. Due to the background interference or the limitations of PD detecting equipment sensitivity, existing techniques and equipment may neglect such PD (or charging phenomena) signals. Such undetected charging phenomena may cause damage to insulation. So it is reasonable to say that it is possible to have damage below the detected DIV.

Conclusions and Prospects

In the present work, iterative method and finite element method (FEM) are used to establish an algorithm with two loops. A typical case is studied, where a solid sheet insulation contains a void. The DIV is calculated by the proposed algorithm with both AC and DC voltage. As the results show, DIV in DC case is much higher than that in AC case. PD under AC conditions are likely to happen in the major axis of the ellipsoidal void, whereas PD under DC conditions are likely to happen in the minor axis.

However, much work and improvements are needed in the future. One possibility is to:

(1) modify the constitutive equations in void based on gas discharge theory, and we may calculate discharge capacity under a different applied voltage, and also,

(2) do some verification experiments. It is proposed that such verification experiments should be performed firstly with voids of considerable size and only afterward with smaller voids.

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