Thoughts on the Possibility of Damage of High-Voltage Electrical Insulation below the So-Called Inception Voltage:

Simulation under a Superposition of AC and DC Voltage – Part III

Jialei Hu
Department of Electrical Engineering
Shanghai Jiao Tong University
Shanghai, China

Jiandong Wu
Department of Electrical Engineering
Shanghai Jiao Tong University
Shanghai, China

M. G. Danikas
Department of Electrical and Computer Engineering, Democritus University of Thrace,
Xanthi, Greece

Yi Yin
Department of Electrical Engineering
Shanghai Jiao Tong University
Shanghai, China

Abstract— **In a previous work, a typical case was studied, where a solid sheet insulation contained a void under DC or AC voltage. In the present paper, a more complex case is studied in order to study the charging phenomenon in HVDC valve windings and cables under a superposition of AC and DC voltages. Real inception voltage is calculated, and it agrees with the experimental results previously reported. Moreover, the location of the charging phenomenon is calculated, and it is correlated to the ratio between AC and DC voltage.**

Keywords-partial discharges; charging phenomena below inception voltage; cavities; simulation

I. INTRODUCTION

For long-distance transmission of electric power, high voltage direct current (HVDC) systems may prove to be less expensive and to suffer lower electrical losses. Converters are the heart of an HVDC converter station, which converts electric power from alternating current (AC) to direct current (DC) or in reverse. Multilevel converters have reached a certain level of maturity, given their industrial presence and successful practical application [1]. The growing market size and increasing technical requirements of MV high-power drives are also pointed out [2]. To achieve a greater capacity, a lower loss and a higher voltage, many researchers study topological structure of HVDC converters [3]. However, in all these topological structures, there is an inevitable problem that the electric field distribution gets more complicated compared to that in common power transformers. For instance, insulations of valve windings and cables are working under a superposition of AC and DC voltage. Some simulation results can be found in [4-6]. The attention given today to HVDC cables appears to be all-time high [7]. It is important to study the electrical behavior under such complicated voltage combinations. Partial discharges (PDs) are one kind of early insulation faults. Through a suitable detection of PD, the recording of partial discharge inception voltage (PDIV) and appropriate study of PD data, insulation –and consequently apparatus- condition monitoring can be carried out, its state can be evaluated and appropriate measures –if there is any need– can be taken. It is interesting that charging phenomena may happen below inception voltage (IV). Due to background interference or the limitation of PD equipment sensitivity, it is possible that PD (or charging phenomena) may occur below the so-called IV [8 – 10].

In a previous work, this phenomenon under AC or DC voltage was discussed from a historical perspective [11]. Simulation was conducted and results showed some differences between the charging phenomena under AC and DC voltage [12]. In the present paper, the aim is to study charging phenomena in HVDC valve windings and cables, which is a more complex case, where a superposition of AC and DC voltage is applied on the insulation sample.

II. MODELING

A. Geometry

The insulation sample used in the simulation is a solid sheet insulation that contains a cavity. Cross section of the sheet is shown in Figure 1. The insulation is a cylinder. Its top surface is in contact with the high voltage electrode, whereas its bottom surface is in contact with the ground electrode. The cavity is a spheroid in the center of the sheet. The sheet diameter is 2R = 20 mm and the height is H=10 mm. The cavity width is 2a = 12 mm and the height is 2b=6 mm. The sample is exactly the same as that in [12]. In the context of this work the terms “void” and “cavity” are used interchangeably. These parallel plate electrodes are widely used in high voltage experiments to test conductivity, permittivity, dielectric loss, space charge and other electrical parameters or behaviors. Such a cavity inside the sample is a typical internal insulation defect. In the case of a cavity containing gas with a lower permittivity than that of the solid, the discontinuity has the effect of increasing the magnitude of the electric field within the cavity. Partial discharges occur if the field exceeds the dielectric strength of the gas in the cavity [13].

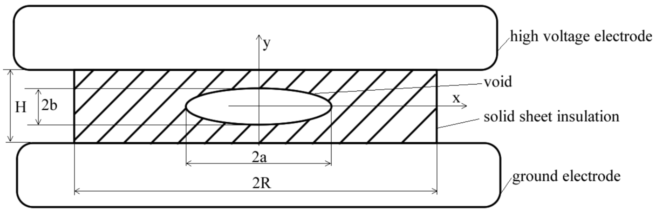

Fig. 1. Cross section of the insulation with a void

B. Materials

The materials used in this simulation are exactly the same as those in [12]. Their electrical parameters are shown in Table I. The insulation sheet is the cross-linked polyethylene (XLPE). In the theory of dielectric physics, the conductivity of XLPE and other polymer solid insulation are affected by electric field and temperature. Two models, namely hopping conductivity [14, 15] and space-charge limited currents [16, 17], give some explanations. Here, it is assume that the sample is in room temperature, so that the conductivity is determined by the electric field. The relationship is shown in Figure 2, which is an experimental result in [18]. Before ionization and breakdown, air is a good insulation with very low conductivity. Here, a typical value of conductivity under standard atmospheric pressure is used for air. Permittivity is an electric parameter to describe the relationship between electric displacement field and electric field. Usually, it is affected by the frequency of the applied voltage. Here, for XLPE and air, typical values under 50 Hz are used.

TABLE I. ELECTRICAL PARAMETERS USED IN THE SIMULATION

material	conductivity (S/m)	relative permittivity
insulation (XLPE)	affected by electric field	2.3
void (air)	5×10^{-14}	1

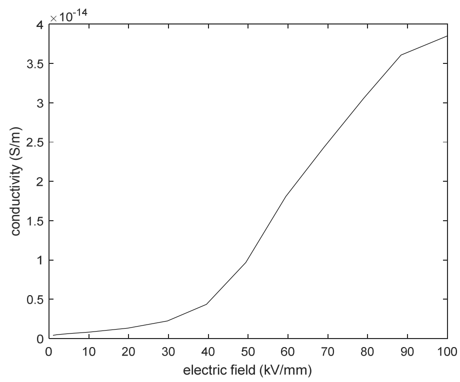

Fig. 2. Electric field vs conductivity of XLPE (after [18])

C. Equations

The electric field under a superposition of AC and DC voltage can be calculated by (1)-(5).

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

$$\nabla \cdot J = 0 \quad (2)$$

$$J = sE + \frac{\partial}{\partial t} D \quad (3)$$

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

$$D = \varepsilon_0 \varepsilon_r E \quad (5)$$

where E is electric field, V is voltage, J is current density, D is electric displacement, t is time, s is conductivity, ε_r is relative permittivity and $\varepsilon_0$is vacuum permittivity. Equation (1) means electric field is an irrotational field in math. Electric field is the negative gradient of voltage. Equation (2) means current field, as the result of charge movement, is a passive field. Eq.(3)divides current into two parts, namely the conduction current and the displacement current. Equations (4) and (5) are constitutive equations. Equation (4) shows that the conductivity is related to electric field, which is demonstrated in Section III.B and is used when calculating conduction current. Equation (5) is used when calculating the displacement current. It should be pointed out that these equations can also be used when only AC or DC voltage is applied. When studying the AC cases, the conduction current is ignored. When studying the DC cases, the displacement current is ignored. In the present case, both parts should be considered, and thus the equations make up a time dependent problem.

D. Conditions and Voltage

Here, two boundary conditions should be applied. One is the high voltage electrode the voltage of which is a superposition of AC and DC, as shown in (6).

$$U(t) = U_{DC} + U_{AC} \sin(2\pi f t) \quad (6)$$

where U_{DC} is the value of DC voltage. U_{AC} is the magnitude of AC voltage. f is frequency and here is set to 50 Hz. The other boundary condition is the ground electrode the voltage of which is set to zero. Since the equations make up a time dependent problem, an initial condition is needed. Usually initial conditions can be set to zero. After a transient process, the solution will reach a steady state. However, it will take some amount of calculation. For the present simulation, the whole process can be accelerated. When we remove AC voltage, the problem becomes a time independent problem and the solving process needs only a little amount of calculation. Then we can set initial conditions for the AC-DC problem to the solution of the DC problem. As a result, this process shortens the transient process.

III. SOLUTION

The solving here is similar to that in [12]. A two loops algorithm is used, as shown in Figure 3. In the outer loop, we set voltages U_{DC} and U_{AC}, and then adjust these values based on the electric field solution, until the maximum electric field in the void equals the break down field strength. The breakdown electric field in the void is set to 3 kV/mm. That is the real IV, or the minimum voltage for charging phenomena. In the inner loop, a voltage distribution is assumed, the conductivity is calculated, the electric field is calculated, and we repeat the two calculation processes until the field distribution does not change. This iteration is a common method when coefficients (such as conductivity) in equations are affected by solutions (such as electric field). The process of calculating the electric field is the main process. It is a traditional Finite Element Method (FEM) problem, which contains geometry, materials, equations and conditions. Here, we use COMSOL Multiphysics software as a Finite Element Analysis solver, and all the algorithms are programmed in it.

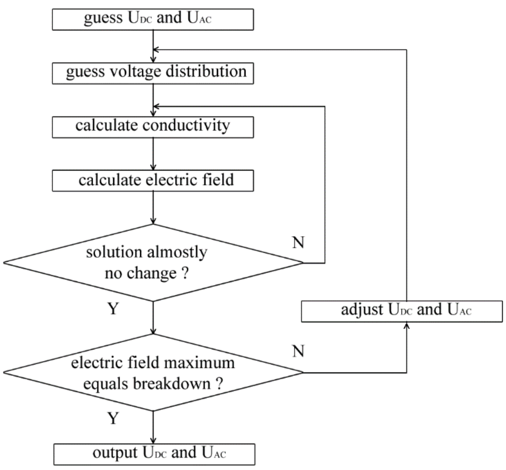

Fig. 3. Process of the two loops algorithm

A. Real inception voltage

A simulation result of the real IV is shown in Figure 4. When the DC voltage is zero, the ACIV is 23 kV. When AC voltage is zero, the DCIV is 160 kV, as can be seen from Figure 4. These results correspond to those reported in a previous work of ours [12]. Under a simultaneous superposition of AC and DC voltage, the IV forms a curve. Below the curve, it is assumed that there is a safe area, where charging phenomena do not occur, and the power system works well. On the curve, whether PD is detected or not, charging phenomena may occur, and the system is considered to be no more safe.

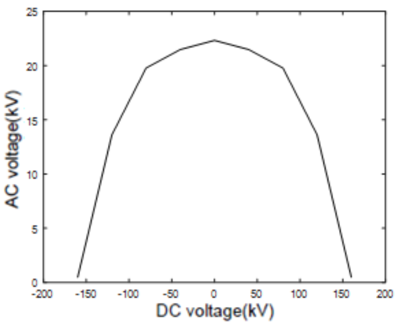

Fig. 4. Simulation results of real IV

The curve is very similar to the experimental result reported in [19], as shown in Figure 5. The experimental arrangement used in [19] was similar to the one used in the present paper. It has to be pointed out, however, that the insulation used in [19] was a composite insulation of oil-paper.To a great extent, the simulation results of Figure 4 show the correctness of the simulation in the presentpaper. It should be emphasized, however, that in this paper the influences of factors such as temperature, space charge, chemical changes were not considered. Needless to say that the actual situation would be far more complicated in reality.

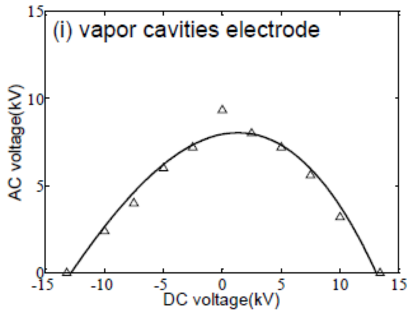

Fig. 5. Experimental results of IV reported in [19]

B. Location of charging phenomenon and further discussion

A typical electric field distribution in the void under a superposition of AC and DC voltage is shown in Figure 6. In Figure 6(a), we have less DC voltage, and the maximum electric field occurs in major axis of the elliptic cross section of thevoid. In Figure 6(b), we have more DC voltage, and the maximum electric field occurs in minoraxis. Such results are in agreement with those obtained in [12], where AC and DC voltages were separately investigated. It is evident that the location of a charging phenomenon is related to the ratio between the applied AC and DC voltages. In other words, the sort of decomposition of a void (either along the major or along the minor axis) may indicate the prevalence of a DC or of an AC component. As was pointed out in [12], under only DC conditions, a much higher high-voltage source is needed in order to have PD in an insulation than when we have an AC voltage applied. Partial discharges are far easier to be recorded with AC voltages. With the advent to the high-voltage engineering applications of more and more of power electronics arrangements, it becomes apparent that superposition of AC and DC voltages may occur and, consequently, new conditions for PD onset may arise.

It has been noted that PD or charging phenomena may or may not be registered, depending on the sensitivity of PD detecting equipment [20]. In this context, Figure 4 of this paper indicates that although the dielectric strength of the air void may be reached, it is by no means certain that something will be recorded by a PD detector. In other words, it is speculated that, although simulation results give the real IV, the latter may be lower than the experimental IV which is recorded. Strong indications and hints to this view already exist [21-24]. Especially in [24], the authors mention that, with very small enclosed voids, PD pulse currents tend to have the lowest values. Whether such low values can be detected by PD equipment depends on the sensitivity of the equipment. It also points out to the fact that there may a need to rethink about our approach as to the PD phenomena in general, since – as discussed long ago – charging effects may take place below the so-called inception voltage, the consequence of which is not yet clear [25, 26]. What some people perceive as self-extinction of PD may well be the inability of a PD detecting device to detect PD of extremely small magnitude (or even charging phenomena) which may be of detrimental nature [27, 28]. Certainly more work has to be done in this direction since, although the criterion for a streamer development in a cavity is that this has to be >0.4 mm, the criterion for a Townsend discharge is that a void has only to be larger than 0.1 micron [29, 30].

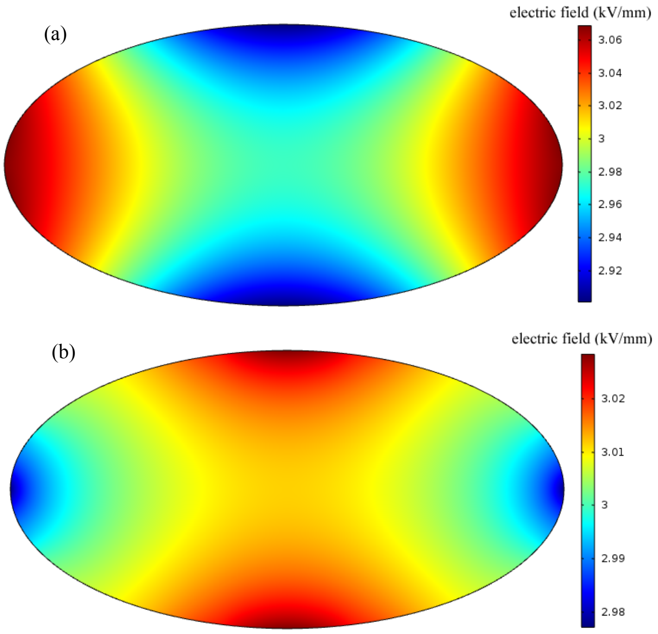

Fig. 6. Electric field distribution in the void. (a) U_{DC}=40 kV and U_{AC}=22 kV (b) U_{DC}=80 kVand U_{AC}=20 kV

IV. CONCLUSION

In this paper, based on previous work, the charging phenomenon in HVDC valve windings and cables was studied, where a superposition of AC and DC voltage is applied on the insulation sample. An iterative method with two loops algorithm is used to solve the time dependent problem. Real IV is calculated, and the results qualitatively agree with experimental results reported in another paper. Moreover, the location of charging phenomenon is calculated, and it is related to the ratio between AC and DC voltage.

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