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Effect of multiple dielectric layers

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INFLUENCE OF BULK DIELECTRIC POLARIZATION UPON PD TRANSIENTS: EFFECT OF MULTIPLE DIELECTRIC LAYERS

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ABSTRACT

A physically valid theory of partial discharge transients has been developed using a field-theoretical approach. The theory is based upon the concept of charge induced upon the detecting electrode by the partial discharge. This induced charge can be resolved into a component associated with the actual space charge in the void and one related to changes in the polarization $\delta\vec{P}$ of the bulk dielectric. These changes are brought about by changes in the field external to the void, which in turn are due to the void space charge. The magnitude of the induced charge component due to $\delta\vec{P}$ is discussed in relation to a three-layer bulk dielectric.

INTRODUCTION

A partial discharge in a gaseous void leads not only to a charge being induced on the detecting electrode, but also to a change in the polarization of the bulk dielectric. This change $\delta\vec{P}$ is reflected in the charge induced upon the detecting electrode [1,2].

The evaluation of the induced charge can be made using either the λ function, or the ϕ function [1]. These functions take account of the dielectric polarization either implicitly (λ) or explicitly (ϕ). Through their use it becomes possible to identify the influence of the change in dielectric polarization upon the induced charge.

Recently the influence of $\delta\vec{P}$ upon the induced charge associated with a two-layer bulk dielectric was examined in detail [2]. The component of the induced charge due to $\delta\vec{P}$ was found to increase or decrease depending upon the ratio of the dielectric permittivities and within which medium the void was located. This increase/decrease is of course reflected in the Poissonian induced charge q.

In the present paper, the behaviour of a three-layer dielectric is examined and compared with that of the two-layer system. Although the presence of the third dielectric modifies the level of response, the induced charge characteristics remain similar to those of the two-layer system.

POISSONIAN INDUCED CHARGE

The charge induced on an electrode can be described in terms of the Poissonian and the Laplacian components [3]. The Poissonian induced charge is that component of the induced charge which is rigidly linked to the space charge source. The Laplacian component is associated with any change in electrode potential. These two components are equal in magnitude but opposite in polarity.

The final value of the Poissonian in-induced charge q due to a partial discharge can be mathematically resolved into two components:

$$q = q_\mu + q_P \qquad (1)$$

where q_μ is the induced charge directly associated with the space charge in the void, while q_P represents the induced charge related to the change in the dielectric polarization due to the field of this space charge [1].

With respect to the detecting electrode, the effect of the void wall charges can be considered as the effect of a dipole of moment $\vec{\mu}$ located within the void [4]. The Pois-

sonian induced charge arising from a dipole is given by

$$q = -\vec{\mu} \cdot \vec{\nabla}\lambda \qquad (2)$$

where λ represents the proportionality factor between the charge in the void and the induced charge on the detecting electrode. The λ function is a solution of the general Laplace equation [1].

Any method of solving Laplace's equation can be used to determine λ. The boundary conditions are $\lambda = 1$ at the detecting electrode, while at all other electrodes $\lambda = 0$. In addition, the condition

$$\varepsilon_+ (\partial\lambda/\partial n)_+ = \varepsilon_- (\partial\lambda/\partial n)_- \qquad (3)$$

must be fulfilled at all dielectric interfaces such as the walls of voids. In (3), λ is differentiated in the direction normal to the interface, and the signs + and - refer to each side of the interface, respectively.

However, if the dimensions of the void are such that $\vec{\nabla}\lambda$ may be assumed constant within the void, then we can introduce another function, λ_0, which represents the λ function in the absence of the void. As λ is a solution of Laplace's equation, then by mathematical analogy with electrostatic fields, the relation between the λ and λ_0 functions is given by

$$\vec{\nabla}\lambda = h\vec{\nabla}\lambda_0 \qquad (4)$$

For the voids under consideration, the parameter h is a scalar which depends on the void geometry and the relative permittivity of the bulk medium in which the void is located. Employing λ_0, the Poissonian induced charge may be expressed as

$$q = -h\vec{\mu} \cdot \vec{\nabla}\lambda_0 \qquad (5)$$

The component of the Poissonian induced charge related to the void space alone is given by

$$q_\mu = -\vec{\mu} \cdot \vec{\nabla}\phi \qquad (6)$$

The proportionality factor ϕ is a solution of the reduced Laplace equation [1]. The boundary conditions are $\phi = 1$ at the detecting electrode and $\phi = 0$ at all other electrodes. Hence from (1), (5) and (6), the polarization component q_p of the Poissonian induced charge may be expressed as

$$q_p = -\vec{\mu} \cdot (h\vec{\nabla}\lambda_0 - \vec{\nabla}\phi) \qquad (7)$$

THE λ_0 FUNCTION

For a homogeneous dielectric system, λ_0 is a solution of the reduced Laplace equation, and hence in such situations λ_0 and ϕ are synonomous. Consequently (7) would reduce to

$$q_p = -(h - 1)\vec{\mu} \cdot \vec{\nabla}\lambda_0 \qquad (8)$$

For a heterogeneous dielectric system, λ_0 will usually be a solution of the general Laplace equation. To study this situation, we consider a planar electrode geometry with a three-layer dielectric. In rectangular coordinates, the electrodes are represented by $z = 0$ and $z = d$. The dielectric interfaces are then taken as $z = s$ and $z = t$, with $s < t < d$. The permittivity of the layer of thickness s is ε_1, that of thickness $(t-s)$ is ε_2 while the remaining layer of thickness $(d-t)$ has a permittivity of ε_3.

If the lower electrode is used as the detecting electrode, then the boundary conditions for the λ_0 function are $\lambda_0 = 1$ for $z = 0$ and $\lambda_0 = 0$ for $z = d$. Thus the λ_0 functions of the three media are given by

$$\lambda_{01} = \frac{B}{A} \qquad (9)$$

for $0 \le z \le s$, where

$$A = \varepsilon_1\varepsilon_2(d-t) + \varepsilon_1\varepsilon_3(t-s) + \varepsilon_2\varepsilon_3 s \qquad (10)$$

$$B = \varepsilon_1\varepsilon_2(d-t) + \varepsilon_1\varepsilon_3(t-s) + \varepsilon_2\varepsilon_3(s-z) \qquad (11)$$

$$\lambda_{02} = \frac{\varepsilon_1\varepsilon_2(d-t) + \varepsilon_1\varepsilon_3(t-z)}{A} \qquad (12)$$

for $s \le z \le t$, and

$$\lambda_{03} = \frac{\varepsilon_1 \varepsilon_2 (d-z)}{A} \qquad (13)$$

for $t \leq z \leq d$. The λ_0 subscripts 1, 2 and 3, refer to the particular dielectric layers.

On differentiating with respect to z, the relevant expressions for the λ_0 gradients are obtained; viz.

$$\vec{\nabla}\lambda_{01} = \frac{-\varepsilon_2 \varepsilon_3 \vec{e}}{A} \qquad (14)$$

$$\vec{\nabla}\lambda_{02} = \frac{-\varepsilon_1 \varepsilon_3 \vec{e}}{A} \qquad (15)$$

and

$$\vec{\nabla}\lambda_{03} = \frac{-\varepsilon_1 \varepsilon_2 \vec{e}}{A} \qquad (16)$$

where $\vec{e}$ is a unit vector in the positive z direction.

For a homogeneous medium $\lambda_0 = \phi$ and thus for a planar system we have

$$\vec{\nabla}\lambda_0 = \vec{\nabla}\phi = -\frac{\vec{e}}{d} \qquad (17)$$

This expression can be obtained from (14), (15) or (16) for $\varepsilon_1 = \varepsilon_2 = \varepsilon_3$.

HETEROGENEOUS DIELECTRIC SYSTEM

To undertake an assessment of the behaviour of a three-layer dielectric system upon PD transients we will assume that the dipole $\vec{\mu}$, associated with the charge which accumulates at the void wall following a partial discharge, is considered a constant in this study. In addition, it will be assumed that the void is more than 10 times its greatest linear dimension from a dielectric interface, such that the $\vec{\nabla}\lambda$ distribution within the void is effectively uniform; i.e. the existence of the interface does not perturb $\vec{\nabla}\lambda$ within the void. This implies that the concept of h is valid and that (4) may be employed.

Variation of q_{Pn}

With respect to the component of the induced charge related to $\delta\vec{P}$, we have upon combining (7) and (5)

$$\frac{q_{Pn}}{q_n} = \frac{-\vec{\mu} \cdot (h_n \vec{\nabla}\lambda_{0n} - \vec{\nabla}\phi)}{-\vec{\mu} \cdot h_n \vec{\nabla}\lambda_{0n}} \qquad (18)$$

where q_n is the Poissonian induced charge of the heterogeneous system, with $n = 1$, 2 or 3 depending on within which layer the void is located.

With the planar geometry, we may regard the dipole moment as being directed away from the coordinate origin in the positive z direction. This moment can then be expressed as

$$\vec{\mu} = \mu\vec{e} \qquad (19)$$

Undertaking the vector operations, (18) simplifies to give

$$\frac{q_{Pn}}{q_n} = 1 - \frac{d\phi/dz}{h_n d\lambda_{0n}/dz} \qquad (20)$$

Hence using (14), (15), (16) and (17) we obtain for a void in medium 1

$$\frac{q_{P1}}{q_1} = 1 - \frac{A}{\varepsilon_2 \varepsilon_3 h_1 d} \qquad (21)$$

$$\frac{q_{P2}}{q_2} = 1 - \frac{A}{\varepsilon_1 \varepsilon_3 h_2 d} \qquad (22)$$

for a void in layer 2, and similarly for a void in layer 3

$$\frac{q_{P3}}{q_3} = 1 - \frac{A}{\varepsilon_1 \varepsilon_2 h_3 d} \qquad (23)$$

As (21), (22) and (23) contain h, then this implies that q_{Pn}/q_n is dependent on the void geometry. In this study we will assume the void shape as spherical, in which case we have

$$h = \frac{3\varepsilon_r}{1 + 2\varepsilon_r} \qquad (24)$$

where ε_r is the relative permittivity of the dielectric layer containing the void.

The variation of q_{Pn}/q_n with $\varepsilon_2/\varepsilon_1$ is shown in Fig.1, with $\varepsilon_r = 4$ and for

several values of ε_{r3}. On this occasion 3 layers of equal thickness $(d/3)$ are considered.

Taking $\varepsilon_2/\varepsilon_1 = 1$ as a reference condition, we see that q_{Pn} either increases or decreases depending upon whether the void is located in a medium of lower or higher permittivity. This behaviour is similar to that of a two-layer system, $viz.$ dependent on the value of $\varepsilon_2/\varepsilon_1$. However, the actual magnitude of q_{Pn} is now influenced by the relative permittivity of the third layer, ε_{r3}. This response can be readily appreciated since, for $\varepsilon_2/\varepsilon_1 = 1$, the 3-layer system becomes effectively a 2-layer system.

As $\varepsilon_r = 4$, then for $\varepsilon_2/\varepsilon_1 = 1$ and $\varepsilon_{r3} = 4$ we have a homogeneous system. Thus with a spherical void, $q_{Pn}/q_n = 0.25$, see Fig.1. Consequently for $\varepsilon_{r3} > 4$, the void is in a (combined) medium of lower permittivity, leading to an increased q_{Pn}/q_n, $i.e. > 0.25$, see Fig.1. Likewise a decrease occurs when the void is located in a medium of greater permittivity, $i.e.$ when $\varepsilon_{r3} < 4$, $q_{Pn}/q_n < 0.25$. The latter reduction is more pronounced than the corresponding increase.

For a fixed void location q_μ is dependent only on $\vec{\mu}$, which is assumed constant in this study. Hence variations in q_p will be directly reflected in the magnitude of the Poissonian induced charge q, see (1).

CONCLUSIONS

In comparison to a 2-layer dielectric system, the introduction of a third dielectric layer can significantly modify the induced charge component associated with changes in bulk dielectric polarization. The nature of these changes is dependent on the relative permittivities of the 3 dielectrics. Consequently, for equipment employing multiple dielectrics, a correct interpretation of PD transients, with respect to discharge phenomena within a void, does not appear to be possible without full knowledge of the permittivities involved.

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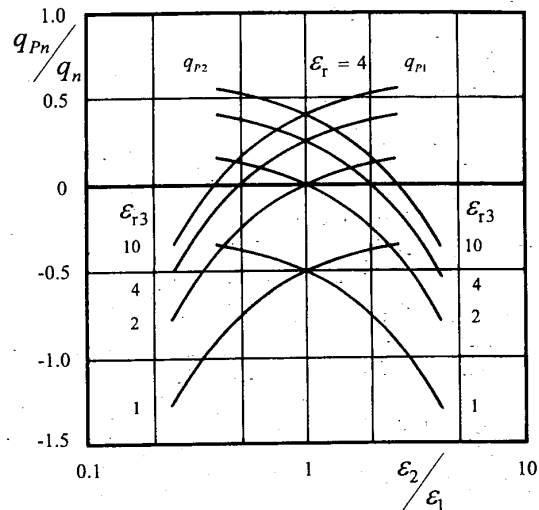
Fig.1 Variation of the polarization component of the Poissonian induced charge.
$(s = t-s = d-t = d/3)$