Electric field determination of polymeric dc power cable in the presence of space charge

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Abstract: Space charge in polymeric power cables has been previously measured by the pulsed electroacoustic (PEA) technique and its influence on electric field distribution has been estimated assuming that the conductivity is independent of electric field. In this paper we proposed a method of determining electric field distribution considering the influence of the effect of electric field on the conductivity. The cable insulation is divided into thin layers with different conductivities and space charge present in the each layer is viewed as the consequence caused by difference in conductivity. Based on the hopping conduction mechanisms, it is possible to compute electric field distribution across the cable insulation. Compared with the electric field distribution without considering change in conductivity, the new proposed method shows reduction at the maximum electric field. However, the position of the maximum electric field shifts depending on space charge distribution.

1 INTRODUCTION

Polymeric dc power cable is one of the areas that have drawn lots of attention recently. Comparing with its counterpart of ac power cable, one of the distinctive features is that the electric field distribution under dc is determined by conductivity of the insulation material. It is well known that the conductivity of an insulating material is dependent of temperature and electric field. This means that the electric field shows changes depending on cable operation conditions. Both cable design engineers and users are keen to know the electric field distribution in order to best utilise the insulation material. Consequently, there have been many attempts to characterise dc electric field distribution in polymeric materials [1-2]. On the other hand, it has been extensively reported that space charge can be easily formed in polymeric insulation materials under dc conditions [3]. As the formation of space charge will distort electric field distribution across the insulation, this makes electric field distribution in dc power cable even more unpredictable.

Following the progress made in non-destructive mapping of space charge distribution in polymeric materials, several techniques have been developed and applied not only to plaque samples but also cable samples. However, the influence of space charge on the electric field in the cable so far has been obtained without considering effect of both temperature and electric field on conductivity.

In this paper we have estimated electric field distribution of XLPE power cable in the presence of space charge considering the effect of conductivity at room temperature. Space charge in a commercial 11 kV ac XLPE power cable under 80 kV dc electric stress was measured using the pulsed electroacoustic (PEA) technique [4].

2 SPACE CHARGE IN POWER CABLE

A section of an 11 kV XLPE cable was prepared for space charge measurement. Space charge was measured using a modified PEA system [5] where a flat ground electrode was utilised instead of curved ground electrode for a conventional cable PEA system [6]. The major advantage of the modified PEA system is easy sample preparation. Compared with the plaque samples, obtaining space charge distribution from the PEA measurement for cable is more complicated and the detailed processes can be found in [5]. A voltage of +80 kV was applied to the central conductor of the cable which has inner and outer radii of 8.75mm and 11.55mm respectively. The voltage was applied for 20 hours to generate sufficient space charge and obtaining the space charge distribution immediately after the removal of the applied voltage as shown in Figure 1.

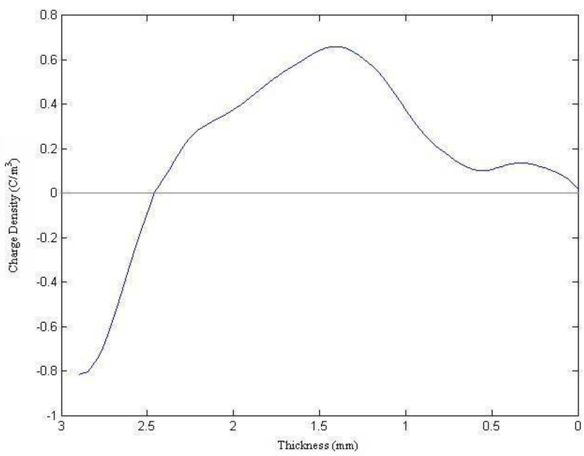

Fig.1 Space charge distribution across the cable insulation after the removal of +80 kV for 20 hours.

It can be seen that significant amount of charges are accumulated in the vicinity of the two electrodes. Positive charge is formed adjacent to the inner electrode (+80 kV) and negative charge close to the outer electrode, indicating that charge injection from the electrodes does take place. It has been reported [7] that significant charge injection takes place when the applied electric field is greater than 25 kV/mm. The applied electric fields in the present case are 32.8 and 24.9 kV/mm for the inner and outer electrodes respectively, therefore the injection is anticipated.

Experimental also revealed that the space charge formed after 20 hours stressing is very stable [8], meaning the charge is deeply trapped.

3 ELECTRIC FIELD DISTRIBUTION

The presence of space charge will produce its own electric field and this field is superimposed onto the applied electric field. Without considering the influence of the field effect on conductivity, electric field can be estimated based on space charge distribution ρ(r) using [5]

$$E(r) = \frac{V_{appl}}{r \ln \frac{r_o}{r_i}} + \frac{1}{r\varepsilon_0\varepsilon_r}\int_{r_i}^{r_o} r\rho(r)dr \qquad (1)$$

where V_{appl} is the applied dc voltage across the insulation, r_o and r_i are radii of the cable at the outer semicon and at the inner semicon respectively. The first term in the right hand side is Laplacian field due to the external applied voltage and the second term is produced by the presence of space charge. As the space charge is stable, the space charge profile after the removal of the applied voltage can be viewed as second term in equation (1). Figure 2 shows the two components and their sum.

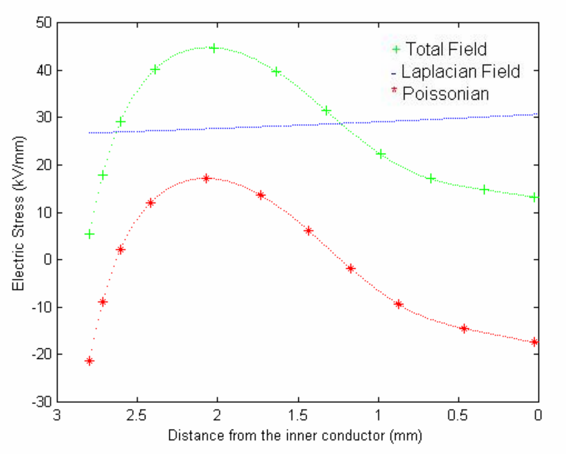

Fig.2 Electric field distribution across the cable insulation in the presence of space charge.

As expected, due to the presence of homocharge the electric field adjacent to the electrodes is reduced while the electric field in the middle of the insulation is enhanced. It is evident that the presence of space charge causes distortion of electric field across the insulation. Higher electric field may lead to local degradation.

Many studies have revealed that the conductivity of polymeric materials is a strong function of temperature and electric field. It has been proposed [2] that conductivity of XLPE can be represented by

$$\gamma(E,T) = A\exp\left(\frac{-\varphi \cdot q}{k_B T}\right)\frac{\sinh(B|E|)}{|E|} \qquad (2)$$

where A and B are constants, φ the thermal activation energy in eV, q the elementary charge, T the temperature in K, E the electric field in V/m, k_B the Boltzman's constant;

The above expression has been employed to compute electric field distribution for cables in the absence of space charge [2]. However, to incorporate the effect of space charge we propose the following: the presence of space charge is a consequence of the mismatch in dielectric properties locally. According to Maxwell-Wagner theory [9], space charge will be formed in the bulk if the material is heterogeneous. So the space charge distribution actually reflects the in-homogeneity of the material. To calculate the electric field in the bulk dielectric considering the effect of conductivity, let us divide the dielectric into many slabs with different values of conductivity and permittivity in each slab to reflect local difference in electrical properties. At steady state a current density J normal to the slabs will have the same value at either side of each slab. The electric flux D in two adjacent slabs will have different values, since the conductivity and permittivity differ in each slab ($D_i = \frac{\varepsilon_i}{\gamma_i}J$, $D_{i+1} = \frac{\varepsilon_{i+1}}{\gamma_{i+1}}J$).

The difference in electric flux will produce charge contained in this subdivision as we know from the relation

$$t\rho_{i+1} = divD = D_{i+1} - D_i = \left[\frac{\varepsilon_{i+1}}{\gamma_{i+1}} - \frac{\varepsilon_i}{\gamma_i}\right]J \qquad (3)$$

Modelling the whole dielectric, as a system of numerous dielectric slabs, we get a profile of space charges through the dielectric. This charge profile should be the same as that measured.

To assess the influence of space charge, the cable insulation is divided into many slabs as shown in Figure 3. The presence of space charge is attributed to the difference in conductivity of each slab.

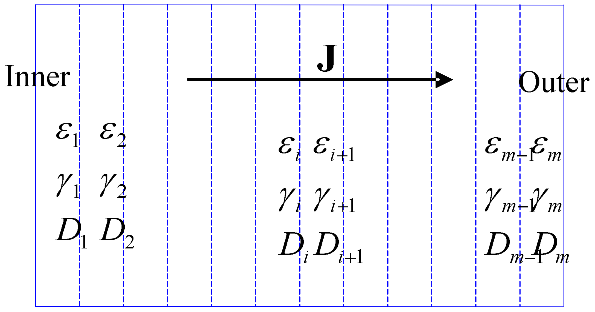

Figure 3 Schematic diagram of space charge modelling for a cable

Substituting conductivity expression into equation (3) gives us

$$\rho_{i,i+1} = \frac{J}{t} \cdot \left[\frac{\varepsilon_{i+1}}{A\exp\left(\frac{-\varphi \cdot q}{k_B T_{i+1}}\right) \frac{\sinh(B|E_{i+1}|)}{|E_{i+1}|}} - \frac{\varepsilon_i}{A\exp\left(\frac{-\varphi \cdot q}{k_B T_i}\right) \frac{\sinh(B|E_i|)}{|E_i|}} \right] \qquad (4)$$

If the space charge density is determined at different distances in the dielectric by the PEA method, the resulting electric field distribution can be solved with the temperature and field effects on the conductivity taken into consideration, using the equation above.

In the present study, we only consider field effect while temperature is kept at room temperature. Experimental evidence shows that the dielectric permittivity ε changes little with electric field and temperature and therefore was assumed constant ($\varepsilon = 2.3\varepsilon_0$)

To calculate electric field using equation (4), we are required to know all the parameters in equation (2). It has been reported [2] that all these parameters are related to the status of polymeric insulation and can vary in a great range. Boggs et al [2] have shown parameters for two extreme cases termed "good" and "bad" dielectrics. In the present study, we have adopted parameters from "good" dielectric.

The initialising value of the electric field at the inner dielectric is derived by the formula [10]

$$E = \frac{V_{appl}}{2\sqrt{r_i}\,(\sqrt{r_o} - \sqrt{r_i})} \qquad (5)$$

This is then substituted into equation (2) to calculate the initialising conductivity. A loop then occurs which solves the new electric field for the corresponding space charge density, electric field, temperature and distance. The calculated electric field is reset as the initialising value, where the new initialising value of the conductivity is calculated, and the loop is repeated again for the whole array of space charge density and corresponding distance and temperature values.

The result is a whole array of the electric field profile, for which a curve is fit and the area underneath is measured. An iteration process is then commenced to shift the curve up or down such that the area beneath it is equal to the applied voltage. This will give the final plot of the electric field strength, which has been compensated for the Laplacian effects and the induced charge effects.

The calculated electric field distribution is shown in Figure 4. Differences have been observed compared with the electric stress distribution in the same cable without considering conductivity effect. Firstly, the maximum electric field becomes smaller i.e. the effect of conductivity tends to moderate the local electric field distribution. Secondly, the position of the maximum electric field shifts towards the inner electrode.

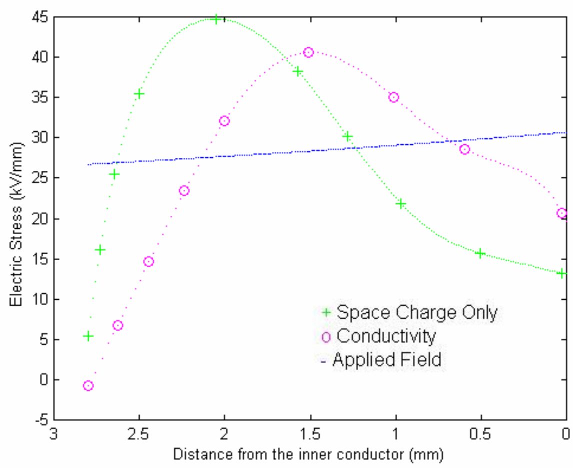

Figure 4 Electric field distribution in XLPE cable under 80 kV.

4 DISCUSSION

The electric field distribution after considering the influence of the conductivity shows a similar trend to the distribution without considering conductivity. However, the maximum electric stress is reduced and its position changes. It has been notified that changes in electric field distribution are highly dependent on the parameters chosen in equation (2). We have adopted a set of values for "good" dielectric in the present investigation. These parameters may not truly reflect the properties of the material, therefore, leading to some errors in electric field distribution. Ideally, a new set of data should be obtained experimentally for the insulation material studied.

Maxwell-Wagner polarisation model is well documented in literature. Charge is accumulated at the interfaces between the conducting and non-conducting regions, thus creating macroscopic polarisation. We have extended the model to two regions with different conductivities and viewed space charge measured in XLPE cable insulation as a consequence of in-homogeneity. Polyethylene is a semi-crystalline material, consisting of crystalline and amorphous regions. They have different properties related to their structures. Situation becomes more inhomogeneous when XLPE is considered due to the addition of di-cumyl peroxide (DCP) and its related by-products. On the microscopic level, the material can be viewed as highly inhomogeneous. Therefore, the adoption of Maxwell-Wagner model in the present study is acceptable.

As mentioned earlier, the conductivity of the insulation generally shows a strong function of temperature. It is anticipated that the electric field distribution will be modified by the temperature. We are in the process of setting up the PEA system to measure space charge distribution in the presence of temperature gradient and will report the results in our future publication.

5 CONCLUSION

A new method based on Maxwell-Wagner model has been proposed to calculate electric field distribution across polymeric dc power cable insulation in the presence of space charge. The proposed method differs from the existing method in which it takes the influence of electric field on conductivity into consideration and therefore gives more true representation of electric field distribution, where it is shown that the maximum electric field is modified and the maximum electric field position shifted. For these reasons, bulk space charge accumulation caused by non-uniform conductivity due to temperature gradient is therefore essential to both cable designers as well as the users.

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