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Calculation of Electric Field Distribution at High Voltage Cable Terminations

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Abstract

High Voltage cables are used for transmission and distribution of electrical power. Such cables are subjected to extensive high voltage testing for performance evaluation and quality control purposes. During such testing, the cable ends have to be prepared carefully to make a proper end termination. Usually deionized water terminations are used for testing XLPE cables. Alternatively conductive paint is used to prepare such a termination. This paper presents an analytical method of calculating the voltage distribution across such a resistive termination when subjected to AC voltage stress. The proposed method is used to determine the effect of different design parameters on voltage and stress distribution on such cable ends. The method is simple and can be used to understand the importance of stress control at a cable termination which constitutes a critical part of such cables.

Keywords: AC voltage distribution, cable terminations, resistive terminations, stress control, XLPE high voltage cable.

1. Introduction

High voltage cables are used extensively for transmission and distribution of electrical power and play an important role in the electricity supply system. Such cables are being manufactured in many countries including Saudi Arabia. These cables are subjected to high voltage testing for routine as well as type tests and for other special investigative tests [1, 2]. Such testing is essential to ensure that the cable's dielectric properties are adequate to meet the specified performance requirements over the expected life time.

The electric field in a coaxial cable varies only in the radial direction as the field magnitude decreases with increasing distance from the conductor center and can easily be calculated analytically. However, when a cable end is terminated for testing and other purposes, the field at such an end region is no longer purely radial and a tangential component is also introduced. Such a tangential field component can cause partial and surface discharges which consequently can lead to breakdown of the cable insulation.

Due to this reason, during high voltage testing of polymeric cables, cable ends are immersed in de-ionized water. Alternatively a conductive paint is applied at the cable end or some other form of resistive-capacitive cable termination is formed to improve the voltage distribution at such ends. The properties and selection of such stress control materials play an important role in the stress control properties of such cable terminations [3-6]. The electric field calculations for cable terminations have been reported in literature [7-10]. However, most of these methods employ numerical techniques and complex computations for the field solutions and do not provide any analytical insight into the stress distributions.

This paper presents a simple analytical method to calculate the voltage distribution at a coaxial cable end where a certain length of the grounded shield is removed and the cable end is enclosed in a resistive medium. Analytical expressions are derived to determine the voltage and tangential electric field distributions at such ends. The effects of different design parameters on the voltage and field distributions are discussed. The proposed method can be used for understanding important concepts related to high voltage cable accessories.

2. **Electric Stress in a Coaxial Cable**

High voltage cables almost always have a coaxial configuration with conductors of inner and outer radii of a and b, respectively. The capacitance C (F/m) of such a cable is given as:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(b/a)} \tag{1}$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m and ε_r = relative permittivity or dielectric constant of the insulation. For XLPE insulation, $\varepsilon_r = 2.3$. When a test voltage V_T is applied across the cable, a charge $q = CV_T$ is produced on the cable's conductor. By application of Gauss's Law, the electric stress E in the coaxial cable insulation at a distance r from the cable center is given as:

$$E_r = \frac{CV_T}{2\pi\varepsilon_0\varepsilon_r r} = \frac{V_T}{r\ln(b/a)} \tag{2}$$

This equation clearly states that the field is purely radial and is confined within the outer conductor. Its value is maximum at r = a and is minimum at r = b.

3. Cable Termination and Stress Distribution

In modern cables, the insulation medium used typically is XLPE which has a high dielectric strength and is capable of withstanding large value of imposed electrical stress. However, at the cable end, if a high test voltage is applied, a flashover will take place in the air between the conductor and the shield since these are relatively very close. To overcome this limitation, the outer conductor and semiconducting screens are removed upto a length L from the cable's end. Due to this modification, the field in the cable's end region is no longer radial and a tangential field component is introduced. This increases the stress value at the ground shield cut back edge. As a result, if no corrective measures are taken, the cable will have electrical discharges and breakdown in such a region. The corrective measures attempt to redistribute stress in the cable's end region.

One common method employed for the corrective measure during the cable testing is to insert the cable ends in an insulting tube containing deionized water of low conductivity. Such deionized water terminators are a common feature of high voltage cable testing facilities. The analysis of voltage distribution along the cable end in such a cable termination is therefore of considerable practical interest and is reported rest. The approach presented is simple and can be easily explained to students and engineers to highlight the stress control issues in a cable termination, which is a very critical component of any high voltage cable system.

4. Method of Analysis

Fig. 1 shows such a simple deionized water termination. Let us assume that at distance x from the cable end, the current in the deionized water is I(x) and voltage is V(x). Let C be the cable capacitance (F/m) and R represents the resistance of the deionized water (Ω/m). Assuming that the insulation resistance of the cable is very large (or infinity), can write the following equations for the one end region:

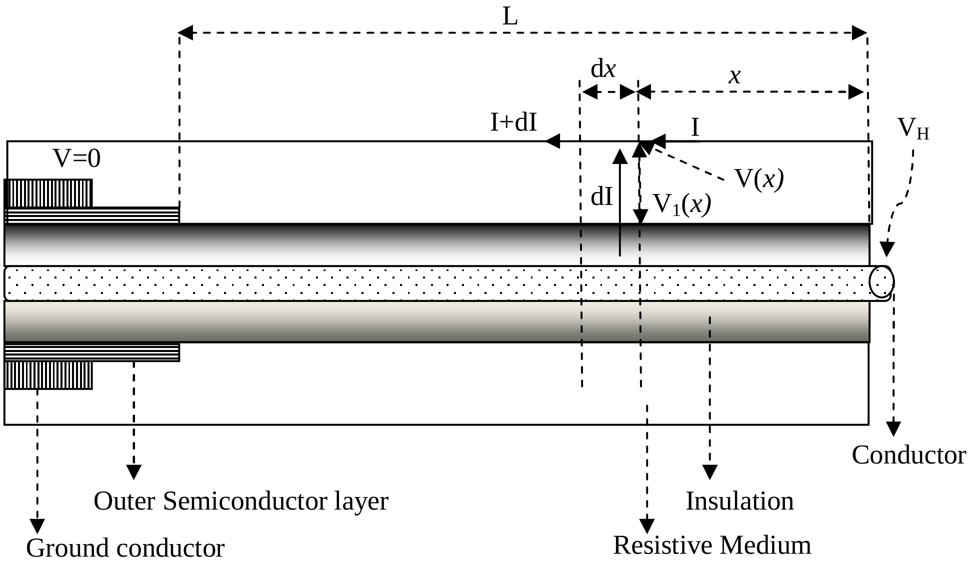

Figure 1. End of coaxial cable

$$\frac{dV(x)}{dx} = -RI(x) \tag{3}$$

$$\frac{dI(x)}{dx} = j\omega RCV_H - j\omega CV(x) \tag{4}$$

In eqns. 3 & 4, ω is the angular frequency of AC voltage and V_H is voltage applied to the conductor. From equations (3) and (4) one can write:

$$\frac{d^2I(x)}{dx^2} = 0 - j\omega C\frac{dV(x)}{dx} = j\omega RCI(x) \tag{5}$$

Equation (5) has a solution of the form:

$$I(x) = A_1e^{\gamma x} + A_2e^{-\gamma x}) \tag{6}$$

Where, $$\gamma = \sqrt{j\omega RC}) \tag{7}$$

and A_1 and A_2 are constants.

From equations (4) and (6), V(x) can be expressed as:

$$V(x) = V_H - \frac{R}{\gamma}\left(A_1e^{\gamma x} - A_2e^{-\gamma x}\right) \tag{8}$$

At x=0, V(x) = V_H, therefore:

$$V_H = V_H - \frac{R}{\gamma}(A_1 - A_2) \tag{9}$$

Hence $A_1 = A_2$. Also, at x = L, V(x) = 0, or

$$0 = V_H - \frac{R}{\gamma}\left(A_1 e^{\gamma L} - A_2 e^{-\gamma L}\right) \tag{10}$$

From eqns. (9) and (10)

$$A_1 = A_2 = \frac{\gamma V_H}{2R\sinh \gamma L} \tag{11}$$

Upon substitution of A_1, A_2 into equations (6) and (8) I(x) and V(x) can be expressed as:

$$I(x) = \frac{\gamma V_H \cosh \gamma x}{R\sinh \gamma L} \tag{12}$$

$$V(x) = V_H - \frac{V_H \sinh \gamma x}{\sinh \gamma L} \tag{13}$$

The tangential stress $E_T(x)$ along the cable insulation surface at distance x can be expressed as:

$$E_T(x) = -\frac{dV(x)}{dx} = \frac{\gamma V_H \cosh \gamma x}{\sinh \gamma L} = RI(x) \tag{14}$$

Moreover, the voltage $V_1(x)$ appearing across the cable’s insulation at distance x from the cable’s end is expressed as:

$$V_1(x) = V_H - V(x) = \frac{V_H \sinh \gamma x}{\sinh \gamma L} \tag{15}$$

6. Results and Discussions

In a typical deionized water termination rated for 300 kVrms, L=2m. In such a termination, if water conductivity is ≈ 0.1μS/cm, then R ≈ 10 MΩ/m. The typically conductivity of deionized water used for testing XLPE cables in such a termination is in the range of 0.01μS/cm to 1μS/cm which corresponds to R value in the range of 1-100 MΩ/m for most cable sizes. For a 15 kV rated, 50 mm^2 XLPE cables, C is about 200 pF/m. For 60 Hz voltage test, ω= 377 rad/s. Figs.2&3 show variation of absolute values of voltages V and V_1 with x for different values of R assuming that V_H = 1V and L = 1m.

The results show that for R = 10 MΩ/m, the voltage distribution is linear along the length L of the cable end. However, as the resistance of the surrounding medium is increased, this voltage distribution becomes non uniform and for R = 10,000 MΩ/m, the distribution is extremely non uniform. Moreover in case of R larger than 155 MΩ/m, the maximum value of V is above 1 due to capacitive effects. Fig.4 shows variations of V with x for a few selected values of L and two values of R (one small, one large).

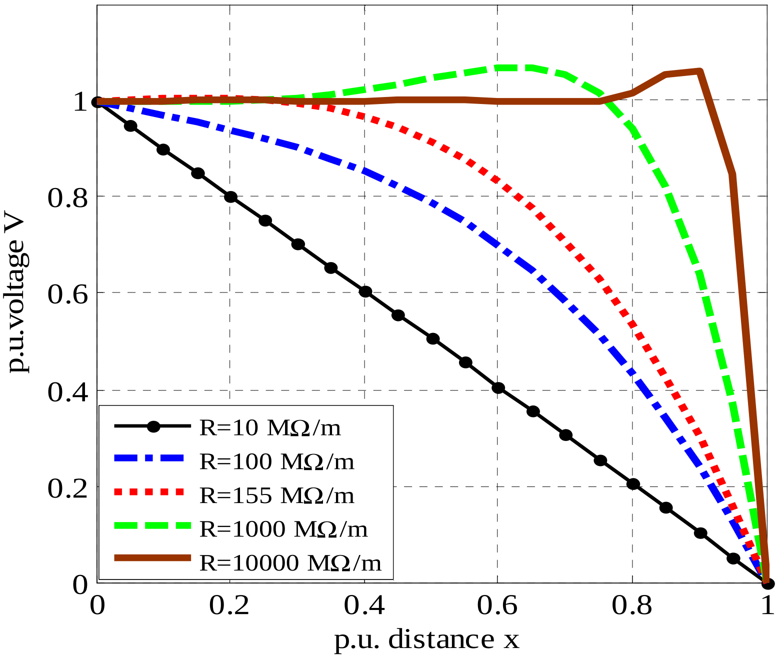

Figure 2. Variation of V with x

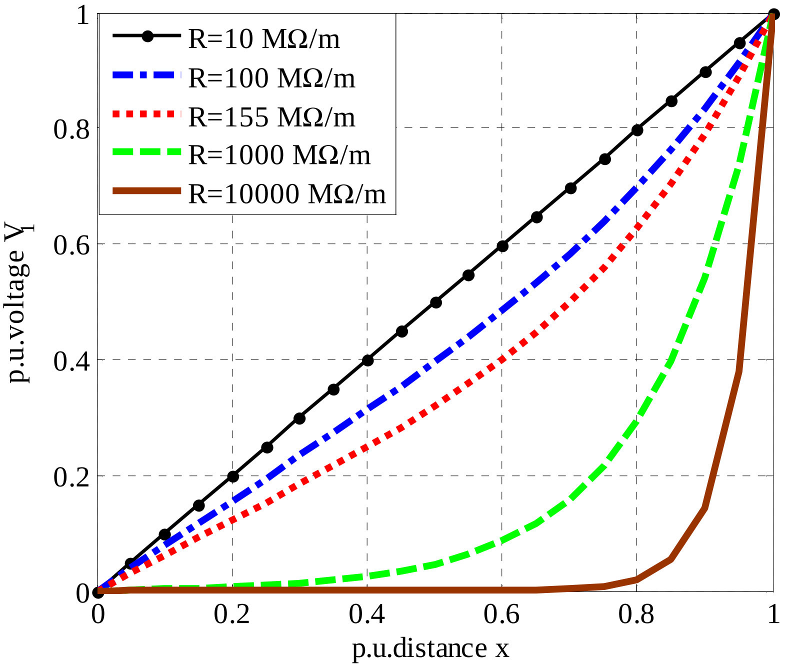

Figure 3. Variation of V_1 with x

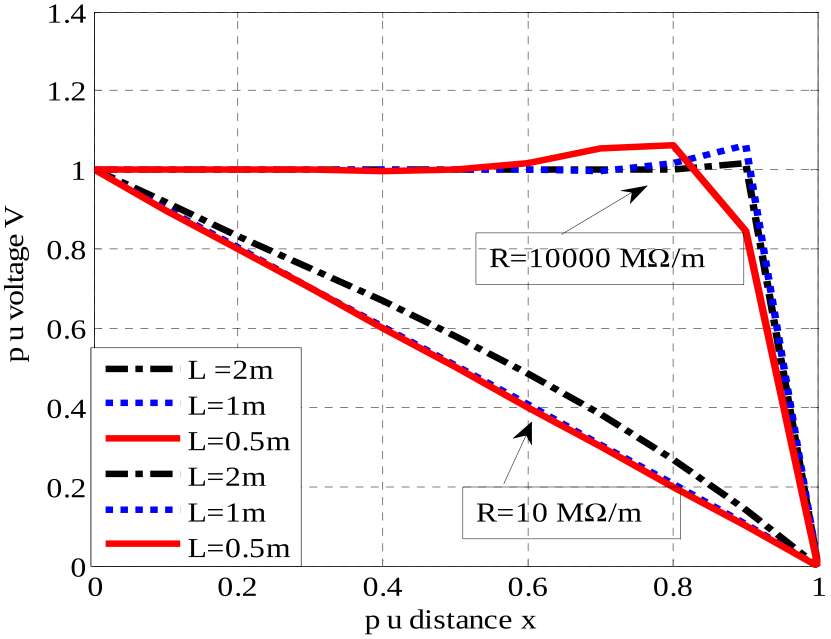

Figure 4. Variation of V with x for low and high values of R

It shows how the voltage distribution is affected by the length of termination in resistive medium as well as the resistance of such a medium. Fig. 5 shows the variation of absolute value of I with p.u. distance x when V_H = 1 volt for different values of R. It shows that for larger values of R, for L=1m and V_H=1V, I is significantly increased near the ground end due to capacitive effects.

The case of R=10,000 MΩ/m means that the cable end is left in an extremely poor conductive medium. The results for this case clearly show that the voltage drop is concentrated only on approximately a few cm near the cut back edge of the shield. Therefore, the tangential stress is very high in this region. Moreover the stress value is very sensitive to the value of R in the region as shown in Fig. 6.

Generally E_T should be kept below 2.5 kV/cm to avoid any surface discharges. To satisfy this condition, low value of R is required since voltage distribution is more linear for a lower R value. However, a lower R value will generate higher power losses in the resistive medium surrounding the cable end. Thus, in the design of such terminations a compromise between tangential stress values and the losses in the resistive medium is required as discussed in literature [9].

The approach presented here for solving the field problem is very similar to the analysis of a long transmission line which is covered in electrical engineering undergraduate courses and is discussed in typical power system text books [11, 12]. The proposed approach can be used to determine the effect of different design parameters on the voltage and stress distributions in such terminations. This method can easily be used to explain the key concepts and challenges associated with the design and use of cable terminations, which represents a critical part of the high voltage cables.

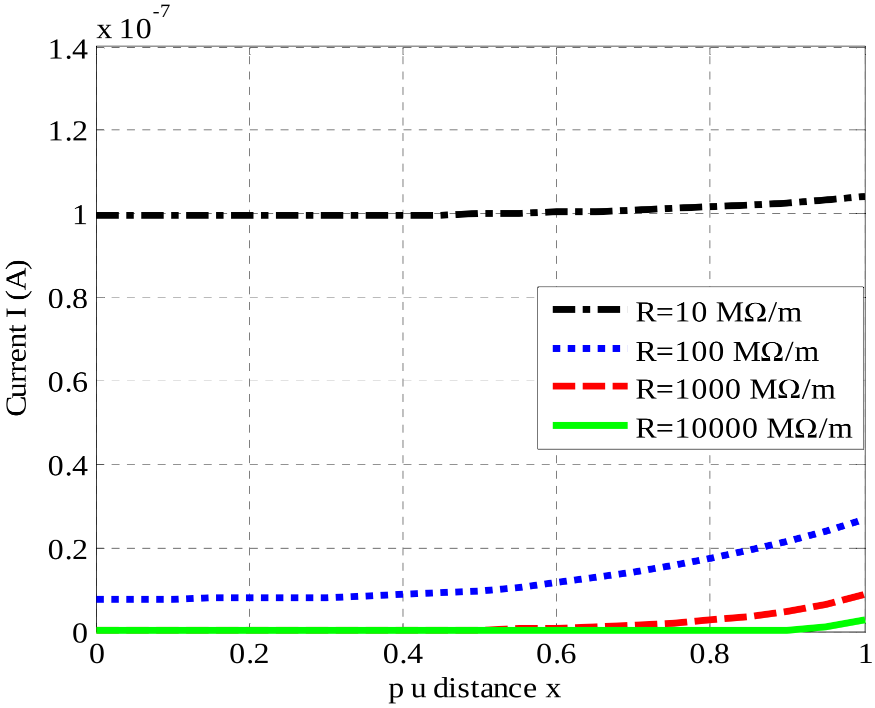

Figure 5. Variation of I with x

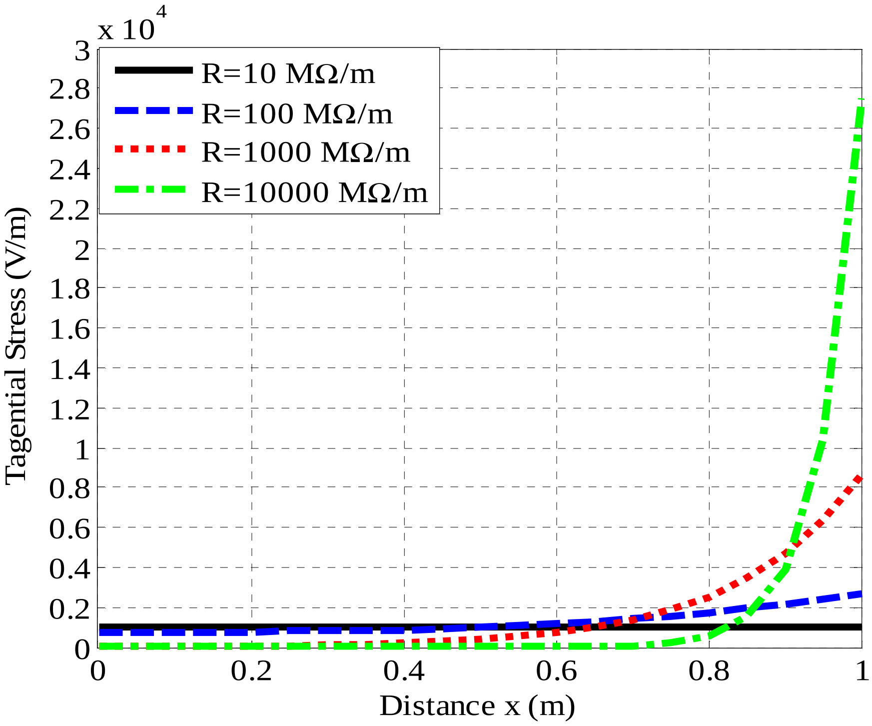

Figure 6. Variation of ET with x when VH = 1V

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2. Conclusion

Using a circuit model for high voltage cable end immersed in a resistive medium, expressions for voltage and stress distributions are derived. The method is simple and can be used to study the importance of electric stress control in cable terminations. The effect of different design parameters on the performance of such a termination is briefly presented.

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