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Research Note

Direct Introduction of Semicon Layers in a Cable Model

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The detection and location of any Partial Discharge (PD) signal requires an accurate frequency dependent cable model to correctly simulate the PD signal attenuation during its propagation in the cable. This model should be capable of simulating the semiconducting layers, which have significant effects on PD signal attenuation and its propagation velocity. There is a substantial need for improvements in the flexibility of the transient cable model through direct introduction of the two semiconducting layers in the cable model. This can be employed in the next step to develop a 3-phase cable model for ATP. This paper has derived an impedance formula for the semiconducting layers. The propagation characteristics of the PD signal, in a cable having two semiconducting layers, are evaluated by applying the derived formula and are compared with the related characteristics in a cable with no semiconducting layer. The propagation of a PD signal applied to the sending end of the core conductor is investigated. In the application of the semicon pick-up sensor in the cable joint, there would be a considerable high frequency voltage across each semiconducting layer, which can be used for the study of PD phenomenon.

INTRODUCTION

While the primary purpose in the application of power cables with solid dielectrics is to deliver the power at 50 or 60 Hz, they are also capable of carrying higher frequency signals reasonably well. Consequently, this capability is likely to be utilized more in the future for such applications as diagnostics, system protection and load management [1]. Another area of application is power line communication, which uses the power grid for signal transmission at a high frequency range, and up to, for example 30 MHz [2]. The electromagnetic traveling waves in power cables are strongly influenced by frequency dependent attenuation, as well as wave shape deformation [3]. Especially in long cable systems, the attenuation can be so high that lightning or switching surge voltages will be mitigated to an innocuous level [3]. Particularly, modeling the admittance of a cable, realizing its insulation and semiconducting layers is very important for accurate simulation of the attenuation at high frequencies [4].

Accurate evaluation of the PD propagation characteristic is one of the major factors in the detection and location of partial discharge in cross-linked polyethylene (XLPE) insulated cables [5]. Progress in the cable insulation design, such as the inclusion of semiconducting layers to have a uniform electric field distribution, resulted in optimum insulation design and a better over-voltage control. However, this causes a significant PD signal deformation during its propagation [5]. To have a fast PD detection system through online monitoring, first, a detectable signal is needed to be picked up at the monitoring terminals, while the above discussed attenuation can obscure the detection process.

The detection and location of any PD signal require:

(i) A verified knowledge of the phenomena which contributes to PD propagation and its deformation,

(ii) An accurate frequency dependent cable model to correctly simulate the PD signal attenuation in the cable,

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(iii) A model capable of simulating the semiconducting layer, which has significant effects on the PD signal attenuation and its propagation velocity [6].

None of the available transient cable models permits the user to directly specify the semiconductive layers. These must, therefore, be introduced by a modification of the input data, as explained in [7,8], for special cases, in which the semiconducting layers are modeled by considering a fictitious thin insulating layer between the conductor layer and the semicon layer, which is substituted for one of the conducting layers (sheath or armor). The validity of this approach has been verified by measurements of up to at least 1 MHz [8,9]. Note that this method will not be applicable for a cable which has two semicon layers and, also, the armor layer. This paper derives an impedance formula for a conductor's semicon screen. The wave propagation characteristic of a PD signal on a cable having semicon layers on its conductor surface are evaluated by applying the derived formula and are compared with those on a cable with no semicon layers. In this work, the cable propagation characteristics are simulated through the application of some routines in MATLAB and it is shown that the induced voltages on the semiconducting layers at the receiving end may be used for detection.

SEMICONDUCTING LAYER PARAMETERS

The main insulation of high voltage cables is based on extruded insulation type and is always sandwiched between two semiconductive layers, which are in contact with the core conductor and the sheath conductor, respectively. These layers are essential, in order that the contact between the conductors and the insulation be excellent (voids lead to partial discharge and progressive deterioration).

The electric parameters of the semiconductive screens can vary between wide limits, due to the high carbon content [10]; the relative permittivity of these semiconducting screens is of the order of 1000. For cables with extruded insulation, the resistivity is required by norm (IEC 60840) to be smaller than 1000 Ωm and 500 Ωm for the inner and outer semiconductive layers, respectively. More often, a much lower resistivity, typically 0.1-10 Ω m, is used by the manufacturer.

SEMICONDUCTING LAYER IMPEDANCE

Conductor/Semiconducting Layer Impedance

A semiconducting layer can be taken into account by using the follow rigorous treatment. In this approach, each semiconductor and related conductor forms a two-layer conductor system [11], which has no insulation between them.

The impedance of a two-layer conductor, consisting of inner conductor 1 and outer conductor 2 (Figure 1), is given in the following form (if considered from the outer view of a two-layer system (e.g. core) [12,13]):

$$Z_{11} = z_{1\text{out}} + z_{2\text{in}} - 2z_{2m} + z_{2\text{out}},$$

$$Z_{12} = z_{2\text{out}} - z_{2m}, \qquad Z_{22} = z_{2\text{out}}. \tag{1}$$

And, if considered from the inner view of two-layer system (for hollow case; e.g. a sheath semiconducting screen):

$$Z_{11} = z_{2\text{in}} + z_{1\text{out}} + -z_{1m} + Z_{12},$$

$$Z_{12} = Z_{22} - z_{1m}, \qquad Z_{22} = z_{1\text{in}}, \tag{2}$$

where Z_{11} is the self impedance of the loop between conductor 1 and the ground, Z_{12} is the coupling impedance of the loop between conductor 1 and conductor 2, Z_{22} is the self impedance of the loop between conductor 2 and the ground, $z_{1\text{out}}$ is the internal impedance (per unit length) of tubular conductor 1 with the return path outside the tube (conductor 2), $z_{2\text{in}}$ is the internal impedance (per unit length) of tubular conductor 2 with the return path inside the tube (conductor 1), z_m is the mutual impedance (per unit length) between inside loop 1 and outside loop 2 and can be obtained according to [13]:

$$z_{1\text{out}} = \left(\frac{m_1\rho_1}{2\pi b}\right)\frac{A}{B}, \quad z_{2\text{in}} = \left(\frac{m_2\rho_2}{2\pi b}\right)\frac{E}{F},$$

$$z_{2m} = \frac{\rho_2}{2\pi bcF}, \qquad z_{2\text{out}} = \left(\frac{m_2\rho_2}{2\pi c}\right)\frac{R}{F}, \tag{3}$$

$$z_{1m} = \frac{\rho_1}{2\pi abB}, \qquad z_{1\text{in}} = \left(\frac{m_1\rho_1}{2\pi a}\right)\frac{I}{B},$$

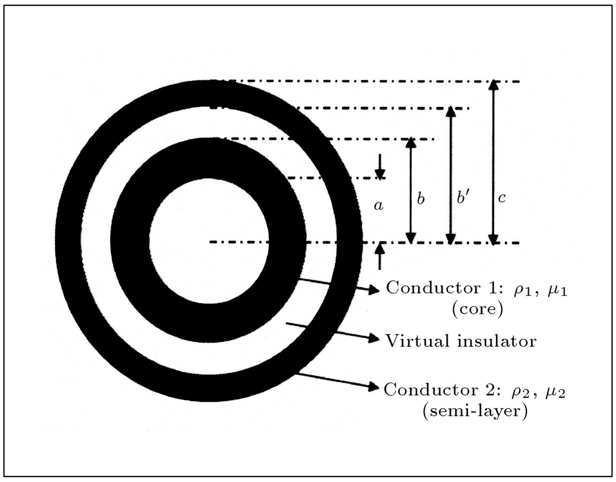


Figure 1. Cross section of a two-layered conductor.

where m is the reciprocal of the complex depth of penetration and μ is permeability:

$$m_i = \sqrt{\frac{j\omega\mu_i}{\rho_i}}, \qquad m_2 = \sqrt{\frac{j\omega\mu_2}{\rho_2}},$$

$$x_1 = m_1 a, \quad x_2 = m_1 b, \quad x_3 = m_2 b, \quad x_4 = m_2 c,$$

$$A = I_0(x_2).K_1(x_1) + I_1(x_1).K_0(x_2),$$

$$B = I_1(x_2).K_1(x_1) - I_1(x_1).K_1(x_2),$$

$$E = I_0(x_3).K_1(x_4) + I_1(x_4).K_0(x_3),$$

$$F = I_1(x_4).K_1(x_3) - I_1(x_3).K_1(x_4),$$

$$R = I_0(x_4).K_1(x_3) + I_1(x_3).K_0(x_4),$$

$$I = I_0(x_1).K_1(x_2) + I_1(x_2).K_0(x_1). \tag{4}$$

And $I_n(x)$, $K_n(x)$ are modified Bessel functions of order n.

Impedance of a Two-Layered Conductor

Since there is no insulation between the semiconductive screens and the corresponding core/shield conductor, it is reasonable to suppose that these two layers are short-circuited. That is why the following equation is obtained [11]:

$$\begin{bmatrix} V \\ V \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{12} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \tag{5}$$

$$I_1 + I_2 = I, \tag{6}$$

where I_1 and I_2 are the currents of the two-layer conductors, respectively, and I is the total current of the conductor. The total outer surface impedance of the two-layer system seen from the sending end is obtained from Equations 3, 5 and 6.

$$Z_{\text{out}} = \frac{V}{I} = \frac{Z_{11}Z_{22} - Z_{12}^2}{Z_{11} + Z_{22} - 2Z_{12}} = z_{2\text{out}} - \frac{z_{2m}^2}{z_{1\text{out}} + z_{2\text{in}}}, \tag{7}$$

and the total inner surface impedance is obtained:

$$Z_{\text{in}} = \frac{V}{I} = \frac{Z_{11}Z_{22} - Z_{12}^2}{Z_{11} + Z_{22} - 2Z_{12}} = z_{1\text{in}} - \frac{z_{1m}^2}{z_{1\text{out}} + z_{2\text{in}}}. \tag{8}$$

The mutual impedance between the inner and the outer surfaces of the two-layer system is given by:

$$Z_m = \frac{z_{1m}.z_{2m}}{z_{1\text{out}} + z_{2\text{in}}}. \tag{9}$$

These equations are used for the consideration of both semiconducting layers on the outer surface of the core and on the inner surface of the sheath.

Impedance of Cable

The impedance of a cable consisted of inner conductor 1, outer conductor and insulation, as seen in Figure 1, is given in the following form [12,13]:

$$Z_{11} = z_{1\text{out}} + z_{12} + z_{2\text{in}} - z_{2m} + Z_{12},$$

$$Z_{12} = Z_{22} - z_{1m}, \qquad Z_{22} = z_{2\text{out}}. \tag{10}$$

Now, conductors 1 and 2 are supposed to be core and sheath, respectively, however, since the semiconducting layers have to be considered, Equations 7 to 9 must be substituted into Equations 10.

CURRENT DISTRIBUTION IN TWO-LAYERED CONDUCTOR

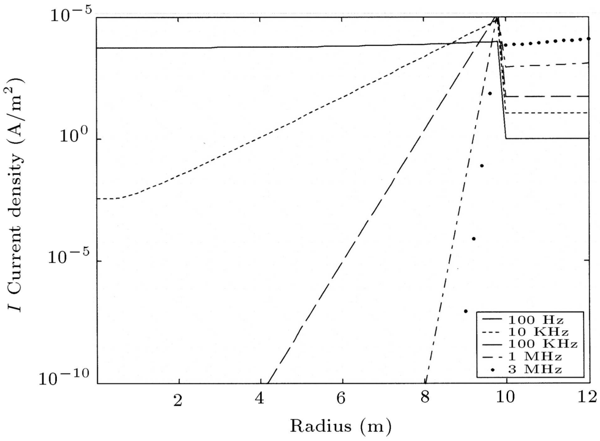
The magnetic and electric fields are obtained from Maxwell's equation for a two-layered coaxial cylindrical conductor [14]. The solutions of the Bessel's equation are combinations of modified Bessel functions and [15]:

$$E_z = A_z I_0(x) + B_z K_0(x). \tag{11}$$

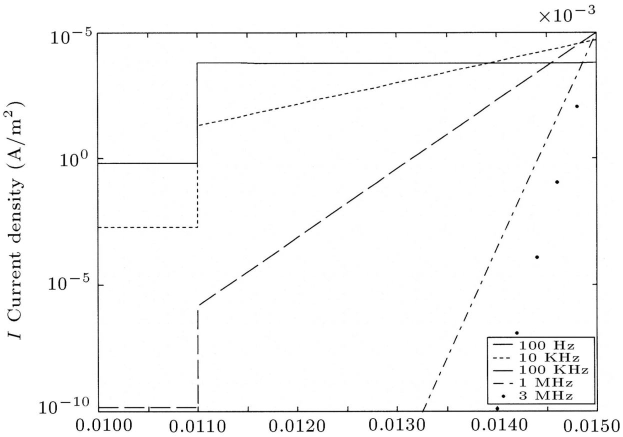
Then, the axial current density distribution within a two-layered conductor is evaluated from E_z, with the coefficients, A_z and B_z, which are determined from the following boundary conditions:

$$i_k(r) = \left\{A_{zk} I_0(m_k r) + B_{zk} I_0(m_k r)\right\} / \rho_k, \tag{12}$$

where $k = 1, 2$ corresponding to mediums 1 and 2, which can be core/semi-layer coupled or semi-layer/sheath coupled. Figure 2 shows the current density distribution of a two-layered coaxial cylindrical conductor when a unit current, 1A, is injected into it. In Figure 2a, a core and a semiconducting layer are simulated and the current density distributions for the different frequencies are obtained. The radius of the core and the thickness of the semiconducting layer are supposed to be 10 mm and 2 mm and the resistivity of the two layers are 1E-8 Ωm and 1E-2 Ωm, respectively. At a high frequency, the largest current flows at the surface ($r = 10$ mm) of the inner conductor, but a large current flows into the outer surface area of the outer conductor, owing to the skin effect, although the resistivity is higher in the outer conductor. In Figure 2b, a similar configuration has been considered for the semiconducting layer and sheath. It can be seen that, at a higher frequency (above 1 kHz), approximately, the whole current flows in the sheath conductor. The thickness of the semiconducting layer and the sheath conductor are supposed to be the same and equal to 2 mm. These figures explain the characteristic of the two-layer conductor at a high frequency, which is important for the behavior of the semiconducting layer at a high frequency.



(a) Core + semiconductor



(b) Semiconductor + sheath

Figure 2. Current density distribution in a two-layer conductor.

SEMICONDUCTING LAYER'S ADMITTANCE

The admittance between the core and the sheath is modeled by using the equivalent circuit, shown in Figure 3, in which each semiconducting screen is modeled by a conductance in parallel with a capacitor. The admittance of a semiconducting layer is given in the following form:

$$y_{\text{semi-in}} = j\omega 2\pi \varepsilon_{\text{semi-in}} / \ln(a/r_1),$$

$$y_{\text{semi-out}} = j\omega 2\pi \varepsilon_{\text{semi-out}} / \ln(r_2/b), \tag{13}$$

where $\varepsilon_{\text{semi}} = \varepsilon'_{\text{semi}} + 1/j\omega\rho$; r_1, r_2, a and b are the outer and the inner radius of the core and sheath and the inner and the outer radius of the main insulation, respectively. Thus the total admittance between core outer and the sheath inner surface is:

$$\frac{1}{Y} = \frac{1}{y_{\text{semi-in}}} + \frac{1}{y_{\text{ins}}} + \frac{1}{y_{\text{semi- out}}}, \tag{14}$$

where $y_{\text{ins}} = j\omega 2\pi \varepsilon_{\text{ins}} / \ln(b/a)$.

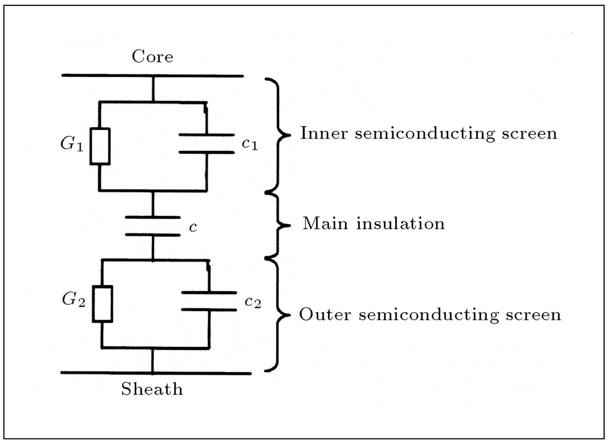


Figure 3. An equivalent RC model for semicons and insulation.

The conductivity and permittivity of the semiconducting screens depend very much on the amount of carbon added, the structure of the carbon and the type of base polymer. Both of them can be strongly frequency dependent. Very high carbon concentrations are used (e.g. 35%). The relative permittivity is very high, typical of the order of 1000.

WAVE-PROPAGATION CHARACTERISTIC OF CABLE WITH BOTH SEMICONDUCTING LAYERS

Core Internal Impedance (Z_{11} in Equation 10)

Figure 4 shows the cross section of an underground 400-kV cable with both a semiconducting layer on the outer surface of a core and on the inner surface of a sheath. Figure 5a shows the real part of the core

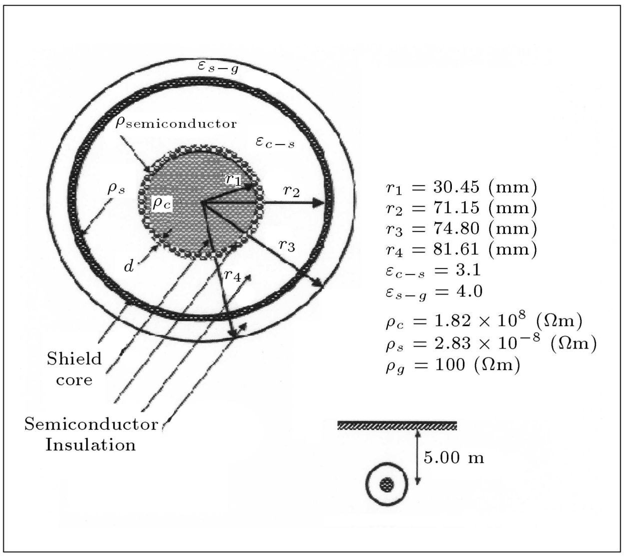
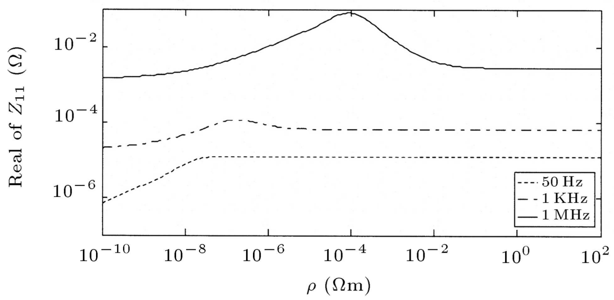
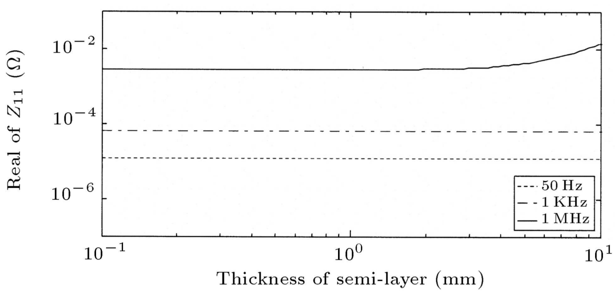


Figure 4. Cross section of an underground 400-kV cable.



(a) As a function of resistivity, ρ (d = 4 mm)



(b) As a function of thickness d (ρ = 0.1 Ωm)

Figure 5. Conductor internal impedance (real part).

internal impedance, with $d = 5$ mm as a function of the semiconducting layer resistivity neglecting the earth. The resistance takes a peak, which becomes more distinctive as frequency increases at a certain value of ρ. The resistivity corresponds to the condition that the penetration depth becomes equal to the thickness of the semiconducting layer.

Figure 5b shows the internal impedance of the conductor as a function of the thickness, d, of the semiconducting layer. At frequencies 50 Hz and 1 kHz, the impedance stays constant at a whole range of the thicknesses in the figure. At a frequency of 1 MHz, the resistance starts to increase at a thickness of about 3 mm. As the resistivity increases, the penetration depth increases and, thus, the impedance is determined almost always by the conductor, i.e., the thickness of the semiconducting layer causes no effect on the impedance. The thickness at which the resistance suddenly starts to rise is related to the penetration depth of the core.

Propagation Constant

The following discussions concern the effect of both semiconducting layers on the wave propagation and the transient characteristic of the cable.

Figure 6a shows the characteristic impedance, the attenuation constant and the propagation velocity of the coaxial mode on the 3-phase 400-kV cable, in Figure 4, as a function of the semiconducting layer resistivity, ρ, with the thickness of $d = 4$ mm. The attenuation constant, α, shows quite a similar characteristic to the resistance of the conductor's internal impedance, as shown in Figure 5a. This is physically quite reasonable, because the attenuation is proportional to the resistance. The propagation velocity decreases and the characteristic impedance (real part) increases as the resistivity increases and becomes constant again. Figure 6b is the frequency characteristic of the propagation constant, which is a typical characteristic of the propagation constants and corresponds to the effect of the resistivity in Figure 6a. The attenuation constant shows no significant difference between the cases of no semiconducting layer and of the resistivity, $\rho = 0.01$ to 100 Ωm, in the frequency range of less than 1 MHz. The effect of the semiconducting layer on the characteristic impedance is not noticeable.

EFFECT OF THE SEMICONDUCTING LAYER ADMITTANCE AND IMPEDANCE

In this section, the propagation constants of the cable are calculated, neglecting the impedance of the semiconductor layers. Figure 7 shows these constants. No significant difference is observed between these characteristics, realizing or neglecting the impedance in Figure 7 for $d = 2$ mm, while for $d = 5$ mm and $\rho = 0.01$ Ωm, a similar difference, as observed between cases 0 and 1 in Figure 6b, is observed. It is important to note that this difference becomes smaller as the resistivity increases.

This study indicates that the effect of the semiconducting layers on the propagation constant is dominated by its admittance, but not by the impedance when the layer thickness is small and the resistivity is high. Therefore, the semiconducting layers can be treated as admittance in most cases, because manufacturers use semiconducting layers with a typical resistivity in a range of $\rho = 0.1$ to 10 Ωm and a thin thickness. However, when the thickness is large and the resistivity is small, then, the impedance should be considered.

SEMICONDUCTING LAYER AS SENSOR FOR PD DETECTION

PD signal propagation is one of the major factors in the detection and location of partial discharge in XLPE cables. In the past, for the PD signal pick-up, an aluminum sheet, interpreted as a capacitance plate, was put on the cable. In this method, the voltage on the capacitive coupling is not sensitive, because most of the high frequency voltage is dropped across the semiconducting layer. In the analysis of high frequency signal propagation (PD signal), the reactance of the equivalent capacitance between the core conductor

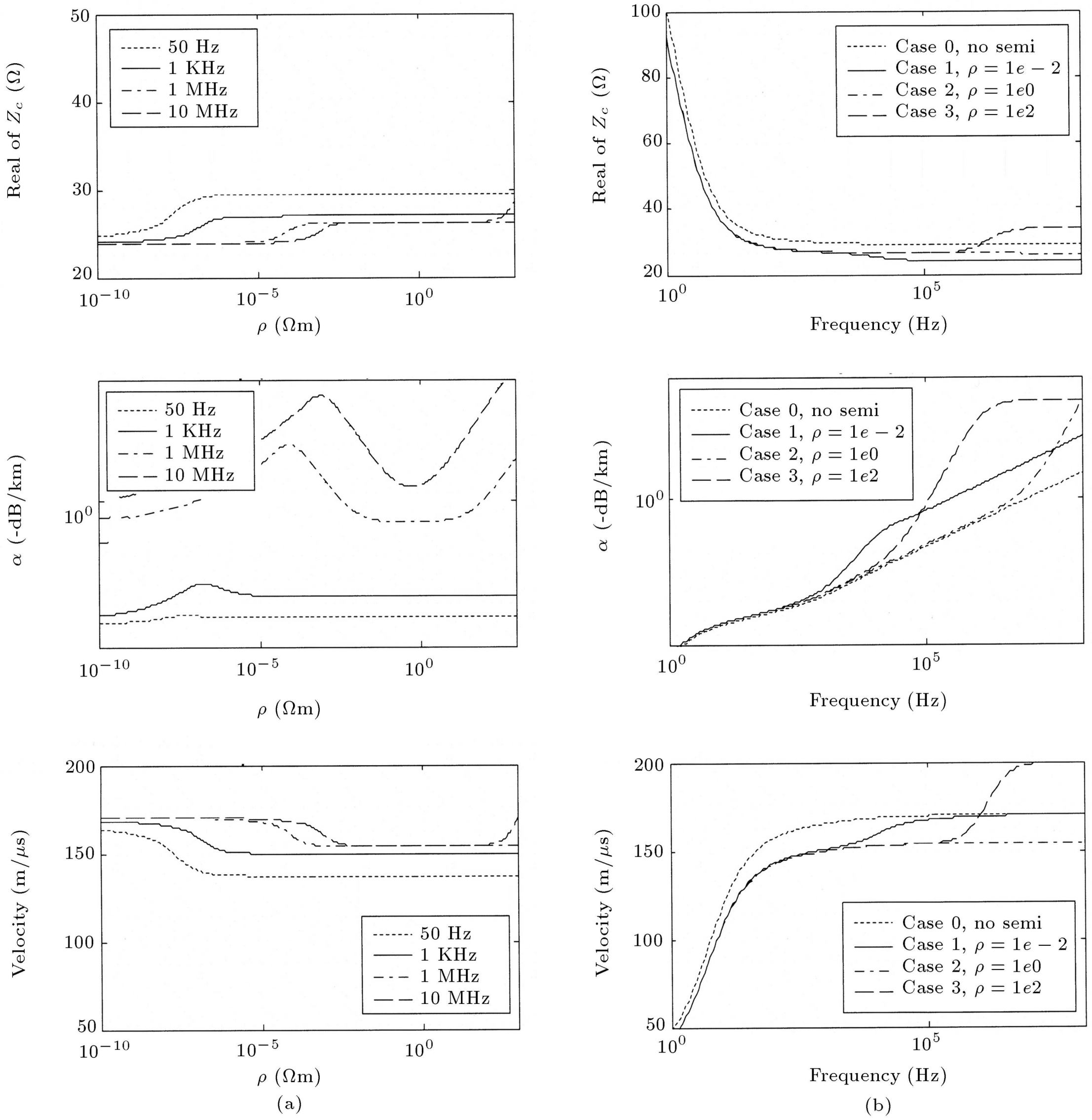


Figure 6. Propagation constants of the coaxial mode of an underground 400 kV cable for $d = 4$ mm. (a) As function of resistivity and frequency; (b) Case 0: No semi-layer; Case 1, 2 and 3: Resistivity according to legend.

sheath copper conductor reduces drastically ($X_c = 1/\omega C$) as frequency increases and, therefore, the voltage division is controlled by the related capacitance, in series with the resistance of the semiconducting layer, which, in this case, are comparable with that reactance.

Figure 8 shows the transient voltage at the receiving end of phase a on an underground 400 kV cable in Figure 4, with length 5 km, when an impulse voltage of a PD signal is applied to the sending-end core conductor on phase a. The cable represented as frequency dependent in the time domain and the PD source signal has a shape, as shown in Figure 9. In Figure 8, the PD signal at the receiving end of the core after one traveling time and the corresponding voltage of the semiconducting layer are shown.

CONCLUSION

This paper has derived an impedance formula for a conductor's semiconducting layer. The PD wave-propagation characteristics, in a cable having both semiconductor layers, are investigated by applying the derived formula for impedance through a well known admittance parameter, and are compared with those in a cable without semiconducting layers. The following remarks are obtained:

A. A metallic conductor and its outer semiconductor layer compose a two layer conductor, whose resistance (the real part of the core internal impedance) shows a peak as a function of the semiconducting layer resistivity. The resistivity, at which the peak appears, corresponds to the penetration depth of

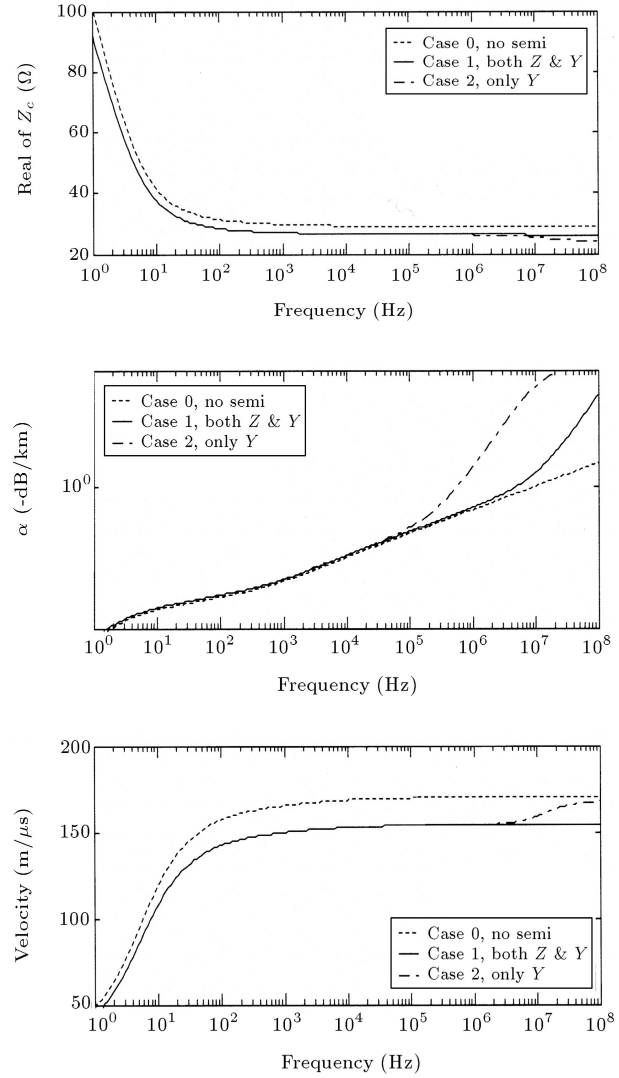


Figure 7. Frequency characteristic of cable ($\rho = 0.1$ Ωm, $d = 4$ mm).

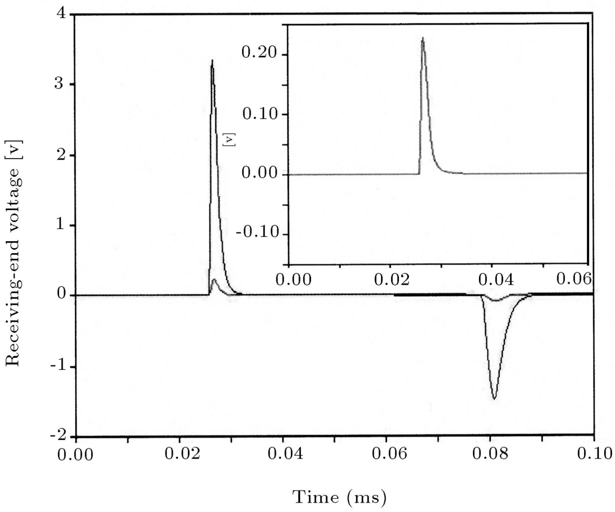


Figure 8. Core and outer semi-layer voltage at the receiving-end.

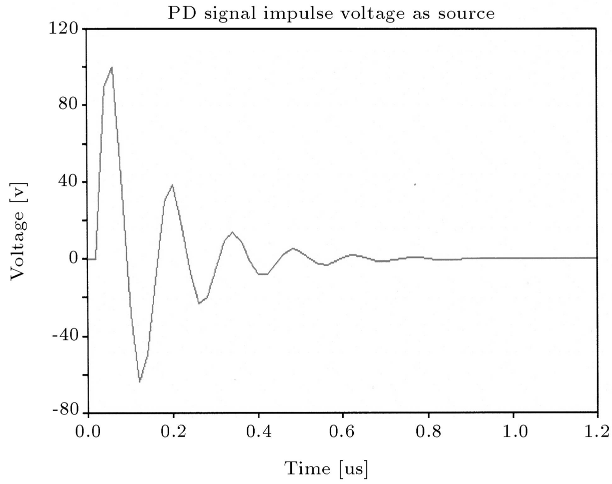


Figure 9. PD signal impulse voltage as source applied to sending-end core conductor on phase a.

the core. The inductance also shows a similar trend, however, the variation is not as significant as in the resistance function;

B. The thickness of the semiconducting layer has a minor effect on the impedance. Since the earth-return impedance of a cable is much greater than the conductor impedance, the effect of the conductor impedance has no significant impact on the total impedance of a cable, i.e., the conductor-self, the conductor sheath-self and the conductor to shield mutual impedances;

C. Most currents flow through the core at a low frequency. A larger current flows through the semiconducting layer, due to the skin effect at high frequencies, although the core resistivity is lower than the semiconducting layer resistivity. This phenomenon for the outer semiconducting layer and the sheath has been reversed and almost the total current flows through the sheath throughout those frequencies, due to the skin effect and the lower resistivity of the sheath conductor;

D. The attenuation constant shows nearly the same trends as the resistivity of the conductor impedance. The propagation velocity and the characteristic impedance of the coaxial mode are lower than those in the case of no semiconducting screen. The former decreases and the latter increases as the resistivity of the semiconducting layers increase;

E. The semiconducting layer decreases the peak value of the received signal and makes the oscillating period longer for a transient voltage waveform on a conductor. This effect becomes more significant when an impulse voltage is applied to the conductor;

F. In the analysis of high frequency signal propagation, the reactance of the equivalent capacitance between the core conductor and the sheath copper conductor reduces drastically as the frequency increases and, therefore, the voltage division is controlled by the related capacitance in series with the resistance of the semiconducting layer, which, then, is comparable with that reactance. That is why the pick-up sensor on the semiconducting screen can be useful for PD signal detection. It is expected to extend this single-phase cable modeling method to model a 3-phase cable.

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