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Citation for published version (APA):

Wagenaars, P., Wouters, P. A. A. F., Wielen, van der, P. C. J. M., & Steennis, F. (2009). Partial discharge propagation in three-core cables with common earth screen. In *Proceedings of the 9th International Conference on Properties and Applications of Dielectric Materials (ICPADM) 5-9 August 2009, Harbin, China* (pp. 433-436). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/ICPADM.2009.5252396>

DOI:

[10.1109/ICPADM.2009.5252396](https://doi.org/10.1109/ICPADM.2009.5252396)

Document status and date:

Published: 01/01/2009

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Partial Discharge Propagation in Three-Core Cables with Common Earth Screen

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Abstract: Online partial discharge (PD) detection and location in cable systems is a valuable tool for the estimation of the condition of the system. Different types of cables are encountered in medium-voltage (MV) connections and appropriate models must be constructed to predict PD signal propagation. For three-core power cables with a single common earth screen a multiconductor transmission line (MTL) model is required. This paper presents an MTL model of a such a cable, including interpretation of the decoupled solution as convenient propagation modes. A complicating factor in the estimation of the transmission line parameters of these propagation modes is the presence of semiconducting layers. These layers have a significant influence on the transmission line parameters. Unfortunately, the dielectric properties of these layers are usually unknown for the frequency range of interest for PD diagnostics. It is shown that nonetheless the characteristic impedance and propagation velocity can be estimated using information available in most cable specifications. The estimated values are validated using pulse response measurements on a cable sample.

Keywords: three-core power cables; partial discharges; multiconductor transmission line; parameter estimation

INTRODUCTION

Partial discharge (PD) diagnostics can be employed to assess the condition of cable systems. For correct interpretation of measured PD pulses a model for the power cable through which they propagate is required. For high frequency phenomena, like PDs, a power cable can be modelled as a transmission line, which is described by its characteristic impedance Z_c and propagation coefficient γ . The γ incorporates both the attenuation coefficient α and the propagation velocity v_p . For single-core cables accurate models have been developed [1, 2]. These methods require accurate information on the cable, most notably the high-frequency properties of the semiconducting layers present in cables with cross-linked polyethylene (XLPE) insulation. A method to estimate Z_c and v_p using only information that is available in a typical cable's data sheet has been described for single-core cables [3].

Three-core power cables with a single, common earth screen have not been studied as extensively. In such a cable multiple propagation modes exist. Therefore, the cable has to be analyzed as a multiconductor transmis-

sion line (MTL). For convenience the solution of the MTL analysis can be interpreted as a shield-to-phase (SP) mode travelling between the conductors and earth screen and two phase-to-phase (PP) modes travelling between two conductors. Similar to single-core XLPE cables the semiconducting screens and swelling tapes also have a significant influence on the transmission line parameters in three-core power cables with XLPE insulation. Methods to estimate these parameters for the SP and PP modes are desired.

This paper describes decoupling the propagation modes present in a three-core cable with common earth screen into an SP and two PP modes. Next, two methods to estimate the Z_c and v_p of these modes are presented. Finally, these estimates are validated by comparing the estimated values with measured values.

THREE-CORE XLPE POWER CABLES

The cable type studied in this paper is a three-core XLPE cable with common earth screen. Three-core cables with each core having its own metallic earth screen are outside the scope since each core can be interpreted as an independent single-core cable. The cable, as depicted in Fig. 1, consists of the following parts:

- Three cores, each having:
 - Conductor with radius r_c
 - Conductor screen, semiconducting layer extruded around conductor with thickness t_{cs}
 - XLPE insulation with outer radius r_{insu} and complex relative permittivity $\epsilon_{r,insu}$
 - Insulation screen, semiconducting layer around insulation with thickness t_{is}
 - Swelling tapes, in this paper considered part of the insulation screen.

Fig. 1: Schematic drawing of a section of a three-core cable with common earth screen

- Filler, the space between the cores is filled with a filling material. This material has virtually no influence on the transmission line parameters.
- Swelling tapes, semiconducting tapes cover all cores and filler.
- Metallic earth screen with inner radius r_s . This screen usually consists of helically wound copper wires.
- Outer sheath, usually PE, has no influence on the transmission line parameters.

TRANSMISSION LINE PARAMETERS

For high frequencies ($f \gg v_p/\text{cable length}$) a coaxial structure such as a power cable can be modelled as a transmission line. A three-core cable with common earth screen has to be analyzed as MTL due to the coupled propagation modes it has. General MTL theory can be found in textbooks, such as [4]. The analysis for a three-core cable is summarized here. The common earth screen is the reference/ground conductor. The voltages on and currents through the conductors are defined as:

$$\mathbf{V} = (V_1, V_2, V_3)^T \quad \text{and} \quad \mathbf{I} = (I_1, I_2, I_3)^T \quad (1)$$

where V_i is the voltage on and I_i the current through the i^{th} conductor.

The per-unit-length impedance matrix $\mathbf{Z}$ is a 3×3 matrix with self impedances Z_s on the diagonal and mutual impedances Z_m off-diagonal. Due to the symmetry in a three-core cable all Z_s are equal and all Z_m are equal. For the admittance matrix $\mathbf{Y}$ the same symmetry considerations apply:

$$\mathbf{Z} = \begin{pmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{pmatrix} \quad \mathbf{Y} = \begin{pmatrix} Y_s & Y_m & Y_m \\ Y_m & Y_s & Y_m \\ Y_m & Y_m & Y_s \end{pmatrix} \quad (2)$$

The voltages $\mathbf{V}$ and currents $\mathbf{I}$ at position z along the cable are related following the differential equations:

$$\frac{\partial}{\partial z} \mathbf{V}(z) = -\mathbf{Z}\mathbf{I}(z) \quad \text{and} \quad \frac{\partial}{\partial z} \mathbf{I}(z) = -\mathbf{Y}\mathbf{V}(z) \quad (3)$$

These equations can be decoupled using a transformation matrix $\mathbf{T}$ which transforms $\mathbf{V}$ and $\mathbf{I}$ to modal voltages $\mathbf{V}_m$ and currents $\mathbf{I}_m$. Since $\mathbf{Z}$ and $\mathbf{Y}$ are cyclic symmetric the transformation matrix is [4, 5]:

$$\mathbf{T} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & e^{j\frac{2}{3}\pi} & e^{j\frac{4}{3}\pi} \\ 1 & e^{j\frac{4}{3}\pi} & e^{j\frac{2}{3}\pi} \end{pmatrix} \quad (4)$$

The diagonalized modal equations become:

$$\begin{aligned} \frac{\partial}{\partial z} \mathbf{V}_m(z) &= -\mathbf{Z}_m \mathbf{I}_m(z) \\ \frac{\partial}{\partial z} \mathbf{I}_m(z) &= -\mathbf{Y}_m \mathbf{V}_m(z) \end{aligned} \quad \text{with} \quad \begin{aligned} \mathbf{Z}_m &= \mathbf{T}^{-1} \mathbf{Z} \mathbf{T} \\ \mathbf{V}_m &= \mathbf{T}^{-1} \mathbf{V} \\ \mathbf{Y}_m &= \mathbf{T}^{-1} \mathbf{Y} \mathbf{T} \\ \mathbf{I}_m &= \mathbf{T}^{-1} \mathbf{I} \end{aligned} \quad (5)$$

The modal characteristic impedance matrix $\mathbf{Z}_{c,m}$ gives the ratio between $\mathbf{V}_m$ and $\mathbf{I}_m$. It can be expressed in terms of $\mathbf{Z}$, $\mathbf{Y}$ and $\mathbf{T}$:

$$\mathbf{V}_m = \mathbf{Z}_{c,m} \mathbf{I}_m \quad \text{with} \quad \mathbf{Z}_{c,m} = \sqrt{\mathbf{Z}_m \mathbf{Y}_m^{-1}} \quad (6)$$

The modal propagation matrix γ_m gives the relation between $\mathbf{V}_m$ at a reference location and $\mathbf{V}_m$ at distance z from that location.

$$\mathbf{V}_m(z) = e^{-\gamma_m z} \mathbf{V}_m(0) \quad \text{with} \quad \gamma_m = \sqrt{\mathbf{Z}_m \mathbf{Y}_m} \quad (7)$$

The modal solution can be interpreted a shield-to-phase (SP) propagation mode and two phase-to-phase (PP) propagation modes. The voltages and currents of these modes are defined as:

$$\begin{aligned} V_{sp} &\stackrel{\text{def}}{=} \frac{1}{3}(V_1 + V_2 + V_3) \quad \text{and} \quad I_{sp} \stackrel{\text{def}}{=} I_1 + I_2 + I_3 \\ V_{pp,1} &\stackrel{\text{def}}{=} V_1 - V_2 \quad \text{and} \quad I_{pp,1} \stackrel{\text{def}}{=} \frac{1}{2}(I_1 - I_2) \end{aligned} \quad (8)$$

The voltage $V_{pp,2}$ and current $I_{pp,2}$ of the second PP channel are the same except that V_2 and I_2 are replaced by respectively V_3 and I_3 .

Combining (4)–(8) the modal characteristic impedance and propagation coefficient matrices can be expressed in terms of the SP and PP channel's characteristic impedances (Z_{sp} and Z_{pp}) and propagation coefficients (γ_{sp} and γ_{pp}):

$$\mathbf{Z}_{c,m} = \begin{pmatrix} 3Z_{sp} & 0 & 0 \\ 0 & \frac{1}{2}Z_{pp} & 0 \\ 0 & 0 & \frac{1}{2}Z_{pp} \end{pmatrix} \quad \gamma_m = \begin{pmatrix} \gamma_{sp} & 0 & 0 \\ 0 & \gamma_{pp} & 0 \\ 0 & 0 & \gamma_{pp} \end{pmatrix} \quad (9)$$

Evaluation (9) using (2) and (6)–(7) yields the transmission line parameters of the SP and PP channel in terms of Z_s , Z_m , Y_s and Y_m :

$$\begin{aligned} Z_{sp} &= \frac{1}{3} \sqrt{\frac{2Z_m + Z_s}{2Y_m + Y_s}} \quad \gamma_{sp} = \sqrt{(2Z_m + Z_s)(2Y_m + Y_s)} \\ Z_{pp} &= 2 \sqrt{\frac{Z_m - Z_s}{Y_m - Y_s}} \quad \gamma_{pp} = \sqrt{(Z_m - Z_s)(Y_m - Y_s)} \end{aligned} \quad (10)$$

PARAMETER ESTIMATION

For accurate modelling of the transmission line parameters detailed knowledge of the cable parameters is required. Generally, the cable manufacturer can supply most, but the complex relative permittivity of the semiconducting layers at high frequencies is usually not available. Measurement of ϵ_r is possible, but is laborious [2]. This section describes methods to approximate the characteristic impedances (Z_{sp} and Z_{pp}) and propagation velocities (v_{sp} and v_{pp}) of the SP and PP channel using information that is readily available. Accurately estimating the attenuation without knowledge of the semiconducting material properties is impossible since the losses in these layers have a large influence on the attenuation.

In order to calculate Z_{sp} , Z_{pp} , γ_{sp} and γ_{pp} from (10) the self and mutual impedances and inductances are required. The impedances are dominated by the inductances ($Z_s \approx j\omega L_s$ and $Z_m \approx j\omega L_m$) and the admittances by the capacitances ($Y_s \approx j\omega C_s$ and $Y_m \approx j\omega C_m$). The values for L_s , L_m , C_s and C_m have to be determined. These parameters can be estimated analytically using conformal mapping [6, 7]. They can also be estimated using numerical methods, such as the boundary element method (BEM) [8].

Conformal mapping estimation

The analytical method used in [6, 7] uses a conformal transformation to calculate the capacitances and inductances for a metal pipe with eccentric conductors. The transformation maps the orthogonal coordinate system to another coordinate system for which a closed form solution is available. The method assumes that the second and third conductor have no influence on the magnetic field lines that result from a current through the first conductor. If the conductors are small relative to the metallic screen radius this assumption holds. For a typical power cable this approximation does not really apply, but nonetheless, the method may provide indicative values with sufficient accuracy. In [9] a more accurate analytical method derived from Poynting's theorem is described. This method, however, is computationally intensive, and has therefore little advantage over the BEM estimation.

The conformal mapping is given by:

$$x' + jy' = \frac{x + jy - s}{x + jy + s} \quad (11)$$

where x and y are the orthogonal x- and y-coordinate, x' and y' are the x- and y-coordinate after transformation, and s is a parameter that is chosen such that after the transformation the eccentric conductor and earth screen become concentric. The parameter s is calculated using:

$$s^2 = c_1^2 - r_c^2 \quad \text{with} \quad c_1 = \frac{r_s^2 - r_c^2 - r_x^2}{2r_x} \quad (12)$$

where r_x is the distance from the center of a conductor to the center of the entire cable and c_1 the x-coordinate of the center of the first conductor. See also Fig. 1 for the definition of these parameters. The conductor radius, earth screen radius and distance from cable center to center of the 2nd and 3rd conductor after transformation (respectively R_c , R_s and R_x) are given by:

$$\begin{aligned} R_c &= \frac{r_c}{c_1 + s} \quad \text{and} \quad R_s = \frac{r_s}{c_2 + s} \\ R_x &= \sqrt{\frac{(c_2 + \frac{1}{2}r_x - s)^2 + \frac{3}{4}r_x^2}{(c_2 + \frac{1}{2}r_x + s)^2 + \frac{3}{4}r_x^2}} \\ c_2 &= \frac{r_s^2 - r_c^2 + r_x^2}{2r_x} = c_1 + r_x \end{aligned} \quad (13)$$

The self- and mutual inductances are given by:

$$L_s = \frac{\mu_0}{2\pi} \ln \left(\frac{R_s}{R_c} \right) \quad \text{and} \quad L_m = \frac{\mu_0}{2\pi} \ln \left(\frac{R_s}{R_x} \right) \quad (14)$$

Compared to the XLPE insulation the semiconducting layers are good conductors. Up to at least several tens of MHz the relative permittivity of the semiconducting layers [2] is much larger than that of XLPE (≈ 2.26). Therefore, the semiconducting layers are considered perfect conductors for the electrical field calculations, effectively shielding one conductor from another. Therefore, the self capacitance C_s is given by the capacitance of a single-core cable, and the mutual capacitance C_m is equal to zero:

$$C_s = \frac{2\pi\epsilon_0\epsilon_{r,insu}}{\ln \left(\frac{r_{insu}}{r_c + t_{cs}} \right)} \quad \text{and} \quad C_m = 0 \quad (15)$$

BEM estimation

For determining the capacitances C_s and C_m the i^{th} conductor is given a potential of 1 V, while the other conductors are set to 0 V. From the electric field distribution the associated charge on the j^{th} conductor is determined. This charge is equal to element c_{ij} of the capacitance matrix $\mathbf{C}$. In order to determine L_s and L_m a current of 1 A is sent through the i^{th} conductor and 0 A through the other conductors. Next, the magnetic field is acquired using a BEM calculation. The magnetic flux coupled by the j^{th} conductor gives element l_{ij} of the inductance matrix $\mathbf{L}$. Alternatively, if the cable does not contain any components with a $\mu_r \neq 1$ the inductance matrix $\mathbf{L}$ can also be obtained from the free-space capacitance matrix $\mathbf{C}_0$ (capacitance matrix when the ϵ_r of all materials is set to one). The relation $\mathbf{L} = \mu_0\epsilon_0\mathbf{C}_0^{-1}$ gives the inductance matrix.

EXPERIMENT

The estimations of Z_c and v_p are validated using a pulse response measurement on a cable sample on a drum. In order to measure the parameters of both the SP and PP channel two pulse response measurements are performed. For the first measurement a pulse is injected between the earth screen and the three conductors together. This measurement results in the SP parameters Z_{sp} and γ_{sp} . In the second measurement a pulse is injected between the earth screen and a single phase while the other two phases are floating. Combined with the results of the first measurement the second measurement yields the PP parameters Z_{pp} and γ_{pp} . The propagation velocity v_p is extracted from the propagation coefficient ($v_p = \omega / \text{Im}(\gamma)$). The tested cable has the following parameters: $r_c = 8.55$ mm, $t_{cs} = 0.8$ mm, $r_{insu} = 12.75$ mm, $\epsilon_{r,insu} = 2.26$, $r_x = 16.13$ mm, $r_s = 30.5$ mm and the length is 351 m.

The measured Z_{sp} and Z_{pp} are plotted in Fig. 2. The estimations using the BEM method and the conformal mapping method are also plotted in the figures. The deviations near 9 MHz are measurement artifacts caused by the fact that the injected pulse is a square pulse with a width of 110 ns ($\approx 1/9 \text{ MHz}$). The measured and estimated propagation velocities of both the SP and PP channel are plotted in Fig. 3. Above 7 MHz the measured propagation

Fig. 2: Measured and estimated Z_c of SP and PP channel

Fig. 3: Measured and estimated v_p of SP and PP channel

velocity becomes unreliable due to the lack of energy in the pulses having travelled back and forth through the cable under test.

The Z_c estimations of both methods are almost equal. The accuracy of the estimation of Z_{sp} is about 10%, while the estimation accuracy of Z_{pp} approximately 5% is. The BEM estimation of the propagation velocity of both channels deviates about 5%. The estimation of the conformal mapping method is less accurate, about 5% for v_{pp} and 15% for v_{sp} .

CONCLUSIONS

A three-core power cable with common earth screen has multiple propagation modes. These modes can be decoupled into three modes: an SP mode travelling between the conductors and earth screen, and two PP modes travelling between two conductors. Due to the geometrical symmetry both PP modes have the same transmission line parameters.

The semiconducting screens and swelling tapes have a significant influence on the transmission line parameters of the cable. Despite the fact that high-frequency material properties are usually not available the charac-

teristic impedance Z_c and propagation velocity v_p of both the SP and PP channel of a three-core XLPE cable with common earth screen can be estimated using data that is found in a typical datasheet. Two methods were presented to estimate these parameters. For Z_{sp} and Z_{pp} both methods given similar results with an accuracy of 5 to 10%. For the propagation velocity of the PP channel the accuracy of both methods is 5%, where the BEM estimation is slightly more accurate than the conformal mapping method. The velocity of the SP channel is estimated with an accuracy of about 5% by the BEM method and an accuracy of 15% by the conformal mapping method.

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