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Estimation of Transmission Line Parameters for Single-Core XLPE Cables

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Abstract -- A power cable model for partial discharge (PD) pulse propagation requires knowledge of all factors influencing the transmission line parameters of the cable (characteristic impedance, attenuation coefficient and propagation velocity). These frequency dependent quantities depend, amongst others, on the dielectric properties of the semi-conducting layers. For existing power cable connections, but often also for newly manufactured cables, these quantities, which vary between different cable types, are not known with acceptable accuracy.

This paper discusses methods to estimate the characteristic impedance and propagation velocity using the cable geometry and the dielectric properties of XLPE, but without using the dielectric properties of the semiconducting layers. Measurements on cable samples show that these approximations are valid with sufficient accuracy. The attenuation of PD signals can only be accurately predicted with detailed knowledge of the dielectric properties of the semi-conducting screens.

Index Terms -- modeling, parameter estimation, power cables, transmission lines, cross linked polyethylene insulation.

I. NOMENCLATURE

α	attenuation coefficient (Np/m)
C	distributed shunt capacitance (F/m)
ϵ_r	(complex) relative permittivity, $\epsilon_r(\omega) = \epsilon'_r(\omega) - j\epsilon''_r(\omega)$
G	distributed shunt conductance (S/m)
L	distributed series inductance (H/m)
R	distributed series resistance (Ω /m)
r_c	conductor radius (m)
r_s	mean earth screen radius (m)
t_{cs}	(semi-conducting) conductor screen thickness (m)
t_{is}	(semi-conducting) insulation screen thickness (m)
v_p	propagation velocity (m/s)
Y	distributed shunt admittance (S/m), $Y(\omega) = G(\omega) + j\omega C(\omega)$
Z	distributed series impedance (Ω /m), $Z(\omega) = R(\omega) + j\omega L(\omega)$
Z_c	characteristic cable impedance (Ω)

II. INTRODUCTION

A model that describes the propagation of partial discharge (PD) pulses through power cable systems is required for certain sensitive PD detection techniques [1]. Further, a good model can assist in the understanding and interpretation of PD measurement on cable systems in general. An essential part of the model of a cable system is a transmission line model of the

cable itself.

An accurate transmission line model of a single-core XLPE cable, such as [2]-[3], requires detailed knowledge of the cable construction and its material properties. This paper discusses how the required output parameters (Z_c , v_p and γ) can be approximated with only input parameters that are readily available.

III. SINGLE-CORE XLPE CABLE

In this paper the following typical construction of a single-core XLPE cable is assumed (see Fig. 1):

1. Aluminum or copper conductor.
2. Semi-conducting layer extruded around conductor (conductor screen).
3. Insulation, most modern MV and HV cables use XLPE.
4. Semi-conducting layer (insulation screen).
5. In many modern cables semi-conducting swelling tapes are wrapped around the insulation screen. Because the electrical properties of this layer are similar to the insulation screen [2], we consider this layer to be part of the insulation screen.
6. Earth screen. Construction of this metallic screen is not the same for all cables. An often-used construction is copper wires wrapped helically around the cable. These wires are held into place by a counter-wound copper tape. An aluminum foil may be wrapped over the wires and tapes.
7. Oversheath, usually polyethylene (PE).

IV. TRANSMISSION LINE MODEL

For high frequencies ($f \gg v_p$ / cable length) a coaxial structure, such as a power cable, can be modeled as a two-conductor transmission line [4]. A two-conductor transmission line can be described in terms of the distributed series impedance Z and the distributed shunt admittance Y . These

Fig. 1. Construction of single-core XLPE cable. 1: conductor, 2: conductor screen (semi-conducting), 3: XLPE insulation, 4,5: insulation screen (with swelling tapes, if applied), 6: (wire) earth screen, 7: oversheath.

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parameters are expressed in terms of the resistance R , inductance L , conductance G , and (complex) capacitance C :

$$Z(\omega) = R(\omega) + j\omega L(\omega) \quad \text{and} \quad Y(\omega) = G(\omega) + j\omega C(\omega) \quad (1)$$

When an EM wave, e.g. a PD pulse, propagates through the cable the ratio between voltage and current is given by the characteristic impedance Z_c :

$$Z_c(\omega) = \sqrt{Z(\omega)/Y(\omega)} \quad (2)$$

The propagation and distortion of a pulse traveling through a transmission line is described by the propagation coefficient γ :

$$\gamma(\omega) = \sqrt{Z(\omega)Y(\omega)} = \alpha(\omega) + j\beta(\omega) \quad (3)$$

The real part of γ is the attenuation coefficient α . This frequency dependent parameter describes how waves attenuate due to losses as they propagate through the transmission line. The propagation velocity v_p can be derived from the imaginary part of γ :

$$v_p(\omega) = \frac{\omega}{\beta(\omega)} \quad (4)$$

V. PARAMETER APPROXIMATIONS

Accurate modeling of the transmission line parameters is discussed in several publications, such as [2]. Unfortunately, these models require detailed knowledge of the cable. Generally, the cable manufacturer can supply most required parameters, but not all. Especially, the complex relative permittivity (ϵ_r) of the semi-conducting layers at high frequencies is usually not available. Accurate measurement of ϵ_r is possible, but complicated [2], [5]. Approximations of the transmission line parameters, using only information that is readily available from the cable manufacturer, are described in this section.

A. Characteristic impedance

The series impedance Z is dominantly determined by the inductance L and the shunt admittance Y by C . Assuming $Z = j\omega L$ and $Y = j\omega C$ (2) reduces to:

$$Z_c(\omega) = \sqrt{L(\omega)/C(\omega)} \quad (5)$$

Substituting L and C with their equations for a coaxial structure [4] yields:

$$Z_c(\omega) = \frac{1}{2\pi} \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r(\omega)}} \ln\left(\frac{r_s}{r_c}\right) \quad (6)$$

The relative permeability μ_r of the insulation and semi-

conducting layers is equal to one. The (complex) relative permittivity of the insulation $\epsilon_{r,insu}$ is not equal to the relative permittivity of the conductor screen $\epsilon_{r,cs}$ and the insulation screen $\epsilon_{r,is}$. Therefore, ϵ_r is replaced by an effective relative permittivity $\epsilon_{r,eff}$. This is the relative permittivity of the homogeneous insulation material of a fictive coaxial capacitor with the same total capacitance and inner and outer radius (respectively r_c and r_s). The capacitance of a single-core XLPE cable is a series of three (complex) capacitances: C_{cs} for the conductor screen, C_{insu} for the insulation and C_{is} for the insulation screen. Fig. 2 depicts the capacitances of the insulation and semi-conducting layers and their relation to the effective capacitance.

For the frequency range of interest (up to 30 MHz for most PD diagnostics on cable connections) C_{insu} is much smaller than C_{cs} and C_{is} because (i) the relative permittivity (both ϵ'_r and ϵ''_r) of the semi-conducting layers is much larger than that of XLPE [2], [5]-[6], and (ii) the insulation is much thicker. Therefore, $C_{cs} \gg C_{insu}$ and $C_{is} \gg C_{insu}$, and thus $C_{eff} \approx C_{insu}$. Because XLPE has extremely low losses $\epsilon_{r,insu} \approx \epsilon'_{r,insu}$. The effective relative permittivity can thus be expressed in terms of $\epsilon'_{r,insu}$ and the dimensions:

$$\begin{aligned} \frac{2\pi\epsilon_0\epsilon'_{r,insu}(\omega)}{\ln\left(\frac{r_s - t_{is}}{r_c + t_{cs}}\right)} &\approx \frac{2\pi\epsilon_0\epsilon_{r,eff}(\omega)}{\ln\left(\frac{r_s}{r_c}\right)} \\ \Rightarrow \epsilon_{r,eff}(\omega) &\approx \epsilon'_{r,insu}(\omega) \frac{\ln\left(\frac{r_s}{r_c}\right)}{\ln\left(\frac{r_s - t_{is}}{r_c + t_{cs}}\right)} \end{aligned} \quad (7)$$

This equation shows that $\epsilon_{r,eff}$ is always larger than $\epsilon'_{r,insu}$. For a typical 240 mm² 6/10 kV cable where $r_c = 9.0$ mm, $t_{cs} = 0.7$ mm, $t_{is} = 0.7$ mm and $r_s = 13.8$ mm $\epsilon_{r,eff}$ is 1.42× larger than $\epsilon'_{r,insu}$. Note that for XLPE insulation $\epsilon'_{r,insu}$ is frequency-independent for the frequency range of interest [7].

Combining (6) and (7) yields:

$$Z_c(\omega) = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\epsilon_0 \epsilon_{r,eff}(\omega)}} \ln\left(\frac{r_s}{r_c}\right) \ln\left(\frac{r_s - t_{is}}{r_c + t_{cs}}\right) \quad (8)$$

The impedance Z_c can now be estimated without knowledge of the dielectric properties of the semi-conducting

Fig. 2. Relation between the complex capacitances $C_{cs} - C_{insu} - C_{is}$ and C_{eff} .

layers. Fig. 3 shows a comparison between the extensive model described in [2], the approximation in (8) and a pulse reflection measurement on a cable sample of 82 m. The cable is a single-core 220 kV XLPE cable with stranded aluminum conductor, a wire screen of 60 wires with a diameter of 1.8 mm helically wound around the cable with a lay length of 1 m. The cable dimensions are $r_c = 28.2$ mm, $t_{cs} = 2.5$ mm, $t_{is} = 2.2$ mm and $r_s = 50.0$ mm. For the XLPE insulation $\epsilon'_{r,insu} = 2.26$ and $\epsilon''_{r,insu} = 0.001$ are used. The values of $\epsilon_{r,cs}$ and $\epsilon_{r,is}$ are taken from [2] (cable 1). The difference between the full model and the approximation is very small, much smaller than the deviation with the measured results.

B. Propagation velocity

Again we assume $Z = j\omega L$ and $Y = j\omega C$. This reduces (3) to:

$$\gamma(\omega) = \sqrt{j\omega L(\omega) \cdot j\omega C(\omega)} = j\omega \sqrt{L(\omega)C(\omega)} \quad (9)$$

Thus the propagation velocity is approximated by:

$$v_p(\omega) = 1/\sqrt{L(\omega)C(\omega)} \quad (10)$$

For homogeneous media $LC = \epsilon_0 \epsilon_r \mu_0 \mu_r$ [8]. Unfortunately, the material between conductor and (wire) screen is not homogeneous. Therefore, ϵ_r is replaced by $\epsilon_{r,eff}$ (7).

Another parameter that affects v_p is the helical lay of the wire screen. Because the coupling between the wires is not very strong the charges of a pulse in the wire screen will mostly follow the helical lay of the wires. Therefore, the pulse must travel some extra distance, resulting in a lower velocity in the direction of the cable axis. Assuming a helical wire screen with a “large” number of wires (> 10) and a straight conductor the multiplication factor for the velocity is given by [9]:

$$F_{hl} = \frac{1}{\sqrt{1 + \left(\frac{2\pi r_s}{l_l}\right)^2 \cdot \frac{1 - (r_c/r_s)^2}{2\ln(r_s/r_c)}}} \quad (11)$$

where F_{hl} is the velocity multiplication factor due to the helical lay of the wire screen and l_l the lay length, this is the longitudinal distance along the cable required for one complete helical wrap. Note that F_{hl} is always larger than the extra length of the helical lay relative to the axial length. This is in agreement with the simulation in [10]. Apparently, the pulses do not exactly follow the helical lay of the wire screen.

Note that (11) does not take into account the following situations:

- Semi-conducting layers. The presence of semi-conducting layers might have an influence on the factor F_{hl} because charges can transfer from one wire to another more easily.
- Stranded conductors. These strands also have a helical lay. Normally, the helical lay length of the conductor strands is much shorter than the lay length of the wire screen, but the capacitive coupling between these wires is much stronger

Fig. 3. Characteristic impedance Z_c : extensive model from [2], result of pulse reflection measurement on cable sample and approximation using (8). For the amplitude the approximation virtually coincides with the complete model and is therefore not visible.

than between the earth screen wires. Therefore, the helical lay of conductor strands is expected to have negligible influence on the propagation velocity.

- Some wire screens with a helical lay do not have a constant angle between wire and cable axis. Instead, the lay angle goes back and forth. In such a situation the propagation velocity is expected to be smaller than without helical lay, but larger than the value calculated by (11).

In literature no information has been found on the influence of the items above on the propagation velocity.

Combining (7), (10) and (11) gives the approximation of the velocity:

$$v_p(\omega) = \frac{c}{\sqrt{\epsilon'_{r,insu}(\omega)}} \sqrt{\frac{\ln\left(\frac{r_s - t_{is}}{r_c + t_{cs}}\right)}{\ln\left(\frac{r_s}{r_c}\right)}} F_{hl} \quad (12)$$

where c is the speed of light in vacuum ($c = 1/\sqrt{\epsilon_0 \mu_0}$). Note

that v_p is independent of the frequency if $\epsilon'_{r,insu}$ is frequency-independent, which is the case for XLPE. Fig. 4 depicts the results of a pulse reflection measurement on a cable sample (same measurement as in previous section), the extensive model prediction [2] and the approximation using (12). In this figure the approximation has a better match with the measurement than the extensive model. This is most likely caused by a systematic error, such as a small error in the cable length for the measurement, or inaccuracies in the radii and/or thicknesses used for the model and approximation.

C. Attenuation

For convenience, the dielectric losses (described by ϵ''_r) are incorporated into G , making C real-valued. Assuming $R \ll \omega L$ and $G \ll \omega C$ yields in combination with (3):

Fig. 4. Propagation velocity v_p : extensive model from [2], result pulse reflection measurement on cable sample and approximation using (12).

$$\alpha(\omega) \approx \frac{1}{2} \left(R(\omega) \sqrt{\frac{C(\omega)}{L(\omega)}} + G(\omega) \sqrt{\frac{L(\omega)}{C(\omega)}} \right) = \alpha_R(\omega) + \alpha_G(\omega) \quad (13)$$

The attenuation is split in two parts: α_R and α_G . The first part, α_R , is the attenuation caused by losses in the conductor and earth screen. Due to the skin effect the conductor and earth screen resistances are proportional to the square root of the frequency, and thus $\alpha_R \propto \sqrt{\omega}$. The second part, α_G , is caused by the losses in the insulation and semi-conducting layers. Because XLPE has a very small loss tangent the losses in the semi-conducting screens are dominant.

Fig. 5 shows a comparison between the attenuation measured on a cable sample (same as in previous sections) and the extensive model. In the same figure also α_R and α_G from (13) are plotted. The measured attenuation is almost 3× larger than the modeled attenuation. The permittivities of the semi-conducting layers of the tested cable were not measured. Instead, they were taken from [2] (cable 1). Most likely the permittivities of the screens in the tested cable are different. In literature it has been shown that there can be at least a variation of a factor 10 in permittivity of the semi-conducting layers of different cables [2], [5]-[6]. In Fig. 5 it can be seen

Fig. 5. Attenuation α : extensive model from [2] (also split in α_R and α_G) and result of pulse reflection measurement on cable sample.

that the dielectric losses (α_G) have a large influence on the attenuation. Therefore, it is impossible to accurately predict the attenuation without accurate knowledge of the permittivity of the semi-conducting layers.

Another factor that influences the attenuation might be additional losses outside the wire screen. Due to the open construction of the wire screen some magnetic field will leak. This field can induce currents in for example the aluminum tape around the wire screen. These induced currents cause extra losses. Also the medium surrounding the cable influence the attenuation [10].

VI. CONCLUSIONS

The semi-conducting layers in a cable with polymeric insulation have a significant influence on high-frequency properties of the cable. Unfortunately, the dielectric properties of these layers at high frequencies are usually unknown and can vary significantly between cables. Therefore, accurate modeling of the transmission line properties is impossible without accurate measurements on samples of the semi-conducting layers. For an installed cable these samples are usually not available.

In this paper, it is shown how the characteristic cable impedance and propagation velocity can be estimated without sensitive measurements or knowledge of the properties of the semi-conducting layers. The approximations are within 1% of the extensive model. Due to the high dependency of the attenuation on the dielectric properties of the semi-conducting layers it is not possible to approximate the attenuation without an accurate estimation of these properties.

VII. REFERENCES

- [1] J. Veen and P.C.J.M. van der Wielen, "The Application of Matched Filters to PD Detection and Localization," *IEEE Electr. Insul. Mag.*, vol. 19(5), pp. 20-26, 2003.
- [2] G. Mugala, R. Eriksson, U. Gäfvert and P. Pettersson, "Measurement Technique for High Frequency Characterization of Semi-conducting Materials in Extruded Cables," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 11(3), pp. 471-480, 2004.
- [3] G. Mugala, R. Eriksson and P. Pettersson, "Dependence of XLPE Insulated Power Cable Wave Propagation Characteristics on Design Parameters," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14(2), pp. 393-399, 2007.
- [4] M.N.O. Sadiku, *Elements of Electromagnetics*, 3rd ed. New York: Oxford University Press, 2001, p. 473.
- [5] C. Xu and S.A. Boggs, "High Frequency Properties of Shielded Power Cable Part 2: Sources of Error in Measuring Shield Dielectric Properties," *IEEE Electr. Insul. Mag.*, vol. 22(1), pp. 7-13, 2006.
- [6] S. Boggs, A. Pathak and P. Walker, "Partial discharge XXII: High Frequency Attenuation in Shielded Solid Dielectric Power Cable and Implications Thereof for PD Location," *IEEE Electr. Insul. Mag.*, vol. 12(1), pp. 9-16, 1996.
- [7] G. Mugala, R. Eriksson and P. Pettersson, "Comparing Two Measurement Techniques for High Frequency Characterization of Power Cable Semiconducting and Insulating Materials," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 13(4), pp. 712-716, 2006.
- [8] C.R. Paul, *Analysis of multiconductor transmission lines*. Chichester: Wiley, 1994.
- [9] D.A. Hill and J.R. Wait, "Propagation Along a Coaxial Cable with a Helical Shield," *IEEE Trans. Microw. Theory Tech.*, vol. 28(2), pp. 84-89, 1980.
- [10] R. Papazyan, P. Pettersson and D. Pommerenke, "Wave Propagation on Power Cables with Special Regard to Metallic Screen Design," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14(2), pp. 409-416, 2007.