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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 XLPE, but without using 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

\( \alpha \) attenuation coefficient (Np/m) 
\( C \) distributed shunt capacitance (F/m) 
\( \varepsilon_r \) (complex) relative permittivity, \( \varepsilon_r(\omega) = \varepsilon'(\omega) - j \varepsilon''(\omega) \) 
\( G \) distributed shunt conductance (S/m) 
\( L \) distributed series inductance (H/m) 
\( R \) distributed series resistance (Ω/m) 
\( r_c \) conductor radius (m) 
\( r_e \) mean earth screen radius (m) 
\( L_c \) (semi-conducting) conductor screen thickness (m) 
\( L_i \) (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 \( (Z_c, v_p, \text{ and } \gamma) \) 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.
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 \( (f >> v_p / \text{cable length}) \) 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

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

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

(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 $Z_c$:

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

(2)

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

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

(3)

The real part of $\gamma$ is the attenuation coefficient $\alpha$. 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 $\gamma$:

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

(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 ($\varepsilon_r$) of the semi-conducting layers at high frequencies is usually not available. Accurate measurement of $\varepsilon_r$ 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 $Z_s$ 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:

$$Z_s(\omega) = \sqrt{L(\omega)/C(\omega)}$$

(5)

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

$$Z_s(\omega) = \frac{1}{2\pi} \sqrt{\frac{\mu_0 L(\omega)}{\varepsilon_0 \varepsilon_r(\omega)}} \ln \left( \frac{r_c}{r_s} \right)$$

(6)

The relative permeability $\mu_r$ of the insulation and semi-conducting layers is equal to one. The (complex) relative permittivity of the insulation $\varepsilon_{r,\text{insu}}$ is not equal to the relative permittivity of the conductor screen $\varepsilon_{r,cs}$ and the insulation screen $\varepsilon_{r,cs}$. Therefore, $\varepsilon_r$ is replaced by an effective relative permittivity $\varepsilon_{r,\text{eff}}$. 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 $r_s$ and $r_c$). 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 $C_s$ 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 $C_s$ because (i) the relative permittivity (both $\varepsilon'$ and $\varepsilon''$) of the semi-conducting layers is much larger than that of XLPE [2], [5]-[6], and (ii) the insulation is much thicker. Therefore, $C_{cs} >> C_{insu}$ and $C_s >> C_{insu}$, and thus $C_{eff} \approx C_{insu}$. Because XLPE has extremely low losses $\varepsilon_{r,\text{insu}} \approx \varepsilon'_{r,\text{insu}}$. The effective relative permittivity can thus be expressed in terms of $\varepsilon'_{r,\text{insu}}$ and the dimensions:

$$\frac{2\pi e_0 \varepsilon'_{r,\text{insu}}(\omega)}{\ln \left( \frac{r_c - t_s}{r_c + t_s} \right)} \approx \frac{2\pi e_0 \varepsilon_{r,\text{eff}}(\omega)}{\ln \left( \frac{r_c}{r_s} \right)}$$

(7)

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

Combining (6) and (7) yields:

$$Z_s(\omega) = \frac{1}{2\pi} \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon'_{r,\text{insu}}(\omega)}} \ln \left( \frac{r_c}{r_s} \right) \ln \left( \frac{r_c - t_s}{r_c + t_s} \right)$$

(8)

The impedance $Z_s$ can now be estimated without knowledge of the dielectric properties of the semi-conducting
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 \( r_s = 28.2 \text{ mm}, \) \( t_{cs} = 2.5 \text{ mm}, \) \( t_{is} = 2.2 \text{ mm} \) and \( r_{cs} = 50.0 \text{ mm} \). For the XLPE insulation \( \varepsilon''_{r,insu} = 2.26 \) and \( \varepsilon''_{r,insu} = 0.001 \) are used. The values of \( \varepsilon_{cs} \) and \( \varepsilon_{is} \) 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:

\[
\gamma(\omega) = \sqrt{j \omega L(\omega) \cdot j \omega C(\omega)} = j \omega \sqrt{L(\omega)C(\omega)}
\]

Thus the propagation velocity is approximated by:

\[
v_p(\omega) = 1/ \sqrt{L(\omega)C(\omega)}
\]

For homogeneous media \( LC = \varepsilon_0 \varepsilon_r \mu_0 H_r \) [8]. Unfortunately, the material between conductor and (wire) screen is not homogeneous. Therefore, \( \varepsilon_r \) is replaced by \( \varepsilon_{r,eff} \) (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 wire screen with a “large” number of wires (> 10) and a straight conductor the multiplication factor for the velocity is given by [9]:

\[
F_{hl} = \frac{1}{\sqrt{1 + \left(\frac{2 \pi r_s}{l_i}\right)^2 \cdot \frac{1 - (r_s/r_c)^2}{2 ln(r_s/r_c)}}}
\]

where \( F_{hl} \) is the velocity multiplication factor due to the helical lay of the wire screen and \( l_i \) 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 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:

\[
v_p(\omega) = \frac{c}{\sqrt{\varepsilon''_{r,insu}(\omega)}} \sqrt{\ln \left(\frac{r_s - t_{is}}{r_s + t_{is}}\right)} F_{hl}
\]

where \( c \) is the speed of light in vacuum \((c = 1/\sqrt{\varepsilon_0 \mu_0})\). Note that \( v_p \) is independent of the frequency if \( \varepsilon''_{r,insu} \) 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 \( \varepsilon''_r \)) are incorporated into \( G \), making \( C \) real-valued. Assuming \( R \ll \omega L \) and \( G \ll \omega C \) yields in combination with (3):

\[
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that the dielectric losses ($\alpha_G$) 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


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: $\alpha_R$ and $\alpha_G$. The first part, $\alpha_R$, 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, $\alpha_G$, is caused by the losses in the insulation and semi-conducting layers. Because XLPE has a very small loss tangent the losses caused by the losses in the insulation and semi-conducting layers of different cables are dominant. Instead, they were taken from [2] (cable 1). Most likely the conducting layers of the tested cable were not measured.

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 $\alpha_R$ and $\alpha_G$ from (13) are plotted. The measured attenuation is almost three times 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 that the dielectric losses ($\alpha_G$) 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.

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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.

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