Cross-bonding cable and box model based on pulse reflection measurement

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Abstract: Transients from lightning strikes can enter underground cables at overhead line to power cable transitions. Possible overvoltages on these surges at cross-bonding connections of the cable screens are of major concern. A model is developed for modelling overvoltages from transient signal propagation through a combined cross-bonding cable and box. This model is applied to the first Dutch 400 kV cable connection. Such model incorporates model parameters whose values depend on design details of the cross-bonding box. The values for these model parameters are extracted from the measured transmission and reflection signal on steep pulses injected into the actual cross-bonding box configuration. The model combines transmission line description for the cross-bonding cables with mainly inductive behaviour of the cross-bonding box. The obtained results are verified by measurements. The model is applied to investigate overvoltages induced at the cross-bonding cable and box on 1.2/50 μs impulse voltage injection representing a lightning impulse voltage applied to the core conductor of the cross-bonding cable. Furthermore, the effectiveness of surge arresters to reduce overvoltages at the cross-bonding cable screen is demonstrated by simulations with this model in PSCAD.

1 Introduction

Underground power cables at a high-voltage level are widely applied nowadays for transmission of electrical energy. All over the world, transmission grid operators are gaining experience with application of cables in their high-voltage power grids. This paper focuses on the Dutch underground cable project ‘Randstad380’. The 380 kV network in the Netherlands is extended by two new connections in which underground cables are combined with overhead lines. The measurements reported in this paper have been scheduled by the Dutch transmission system operator (TSO) during the installation of the first connection, which became operational in 2013. During normal operation, the power grid can be subjected to different transient phenomena, which can largely influence installed equipment. For instance, fast transients from lightning strikes can result in steep voltage surges in the system affecting the installed transformers [1, 2]. The presence of underground power cables in the high voltage (HV) grid will have an influence on the behaviour of the network during fast transients. In particular, there is concern for effects on cross-bonded earth screens, installed for reduction of losses because of induced currents [3]. Transient overvoltages on overhead lines reach the cable at the transition point, where they partly reflect and partly transmit into the underground cable. At cross-bonding (CB) joints, the transient pulse splits in all available channels (Fig. 1). The 400 kV cable earth screens are connected via coaxial cables to a dedicated box with the CB connections. This box can be regarded having zero impedance connections for power frequency. For high-frequency components the box behaves inductively, contributing to overvoltages [4] which stress the CB joint possibly resulting in degradation of the insulation material.

Researching the transient behaviour of underground power cables focuses on cable modelling, which is needed to support simulation studies. Frequency-dependent distributed travelling wave models are generally used for transient modelling and several cable models are developed in [5, 6]. Description of cable impedance, admittance, including the effect of semi-conducting layers has been published in [7]. Modelling of transients requires accurate determination of involved parameters [8, 9]. Currently, a widely used transient cable model is the frequency-dependent phase model [10]. This model is implemented in the electromagnetic transient including DC-based simulation software of power system computer aided design (PSCAD). For research on the transient phenomena of underground cable systems, it is essential to include cross bonding. A CB cable connects the earth screens of the 400 kV cable to the CB box, where the CB connections...
are made, Fig. 1 [11]. Much experimental work and simulations have already been published on modelling of cross-bonded high-voltage cable systems, for example, in [12, 13]. Verification of simulation results with field measurements has been made for CB cable systems [14, 15].

This paper presents a frequency-domain model of the CB cable and the CB box which can easily be implemented for analysis of transmission networks. The values of the model parameters are obtained by pulse injection measurements conducted on the actual applied components at various stages during the construction of the Randstad380 south-ring connection. Special care was taken to prevent any risk of damage to the components by connecting the test equipment. Time-domain measurement by pulse injection method was preferred as a measurement technique since connection issues could be resolved by relatively simple adapters (see Appendix). Furthermore, it is more robust against electromagnetic disturbance, for example, from active parallel overhead lines, compared with frequency-domain measurements with a vector network analyser. For field measurements on large systems (as, for example, applied in [16]) pulse injection techniques are easier and safer to implement. With the developed model, simulations are performed to investigate the influence of steep voltage surges on the generated voltages at the CB box. Also the effect of surge arrestors at the CB earth screens is investigated.

2 Methodology

High-frequency components in, for example, lightning surges are of most concern. They propagate through the 400 kV cable before reaching the first CB joint after a transition point, limiting the frequency components reaching the CB joints. The attenuation is related to the skin effect in the conductors, which forces the current to flow in a smaller conductor area as frequency increases [6, 17]. Also semi-conducting layers can contribute to frequency-dependent losses [7]. CB cables are analysed as transmission lines with frequency-dependent parameters determined from measurement. The total length of the connections inside the CB box itself is about 1 m. Since the signal propagation time inside this box is short, the box can most conveniently be modelled by lumped component parameters for frequencies up to several tens of megahertz.

Transmission line parameters of the CB cables and the impedance of the CB box are measured by means of detecting reflection patterns. First, the transmission line parameters of a CB cable (characteristic impedance \( Z_{cb} \) and propagation coefficient \( \gamma_c \)) are obtained from the reflection measurements indicated in Fig. 2a. Thereafter, the CB cables are connected to the CB box (Fig. 2b). Analysis of reflection measurements on CB cable including the CB box, using the earlier determined parameters \( Z_{cb} \) and \( \gamma_c \), results in the impedance of the CB box \( Z_{cbbox} \).

3 Analysis of CB cable

To establish the effect of the CB box, we need first to characterise the CB cables which are standard connected to the box. On one hand, owing to their short length, transients will hardly be distorted during propagation. On the other hand, because its effect is small, the propagation parameters are harder to determine.

The CB analysis is performed according to the following steps. The reflection coefficient \( r_o \) is related to the impedance transition from injection cable to CB cable. Its value is needed to analyse \( Z_{cb} \). Next, the transmission coefficients from injection cable to CB cable (\( \tau_{bc} \)) and from
CB cable to injection cable ($\tau_{cb}$) are determined for the analysis of $\gamma_{cb}$ and $Z_{cbbox}$.

### 3.1 Estimation of CB cable parameters

Fig. 1c shows the CB cable cross-section, including its dimensions. Characteristic impedance $Z_{cb}$ and propagation velocity $v_{cb}$ (derived from $\gamma_{cb}$) are calculated from (1) and (2), respectively, assuming homogeneous cross-linked polyethylene (XLPE) insulation for the entire cable with $\varepsilon_{XLPE} = 2.25$

\[
Z_{cb} = \frac{1}{2 \pi} \sqrt{\frac{\varepsilon_0}{\varepsilon_{XLPE}}} \ln \frac{r_2}{r_1} = 19 \ \Omega \quad (1)
\]

\[
v_{cb} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_{XLPE}}} = 200 \ m/\mu s \quad (2)
\]

The calculated values will serve as reference for the values obtained from measurements (see Table 1).

### 3.2 Measurement of $Z_{cb}$

The length of each CB cable (Fig. 2) is 12.3 m. The pulse width must therefore be taken relatively short (8 ns for the present investigation) to avoid overlapping the reflected pulses as a consequence of short propagation time from $a$ to $a'$ and back. The pulse ($Y_{inj}$) travels through the injection cable. At $a$ it will partially reflect (reflection coefficient $r_a$) and transmit. Thereafter, the transmitted fraction reflects on the open cable end $a'$. The reflection ($Y_a$) on CB cable end $a$ (Fig. 1) is applied for the analysis of $Z_{cb}$

\[
Z_{cb} = Z_0 \frac{H_{inj} + H_1}{H_{inj} - H_1} - Z_s \quad \text{with} \quad H_1 = \frac{Y_a}{Y_{inj}} = H_{inj} r_a \quad (3)
\]

Here, $H_{inj}$ is the transfer function of the injection cable, $H_1$ is the transfer function of the reflection on CB cable end $a$ and $Z_s$ is the impedance of the adapter (Fig. 2) connecting the injection cable and CB cable ($H_{inj}$ and $Z_s$ are determined during prior calibration, see Appendix). The characteristic impedance $Z_{cb}$ is plotted up to 10 MHz in Fig. 3. An average value of about 17 $\Omega$ is found, while a value of 19 $\Omega$ is calculated from (1). As indicated by (18) in Appendix, the observed deviation can be attributed to measurement error propagation when the impedances clearly differ and to the short CB cable length. This prevents separating injected and reflected completely in the measured record resulting in a relatively high uncertainty in $H_1$. Moreover, the impedance calculated using (1) has an uncertainty because both the conductor and the earth screen are not solid. With an insulation thickness of only 6.0 mm an inaccuracy in $r_1$ or $r_2$ has a significant effect.

### 3.3 Measurement of $\gamma_{cb}$

The reflection on cable end $a'$ (Fig. 1) is applied for analysing the propagation coefficient $\gamma_{cb}$. From the transfer function $H_2$ denoting the reflection on open cable end $a$

\[
H_2 = \frac{Y_{a'}}{Y_{inj}} = H_{inj} \tau_{ci} \tau_{ce} e^{-2\gamma_{cb}} \quad (4)
\]

$\gamma_{cb}$ can be derived

\[
\gamma_{cb} = \frac{1}{2 \gamma_{cb}} \ln \left( \frac{H_{inj} \tau_{ci} \tau_{ce}}{H_2} \right) \quad (5)
\]

The propagation coefficient consists of the attenuation ($\alpha$) and the phase coefficient ($\beta$). The attenuation coefficient is plotted in Fig. 4, which corresponds to an attenuation of $< 1\%$ over a length of 12.3 m. The short CB cable, and consequently short propagation time back and forth on the CB cable, makes the measured attenuation in Fig. 4 to be indicative only. It also hampers precise determination of the characteristic impedance since it is not possible to completely separate the injected pulse from the reflection in a measured record (compare measurements on 400 kV cable presented in Appendix).

The slope of the phase coefficient plotted in Fig. 4 is related to the propagation velocity ($v_{cb}$) according to

<table>
<thead>
<tr>
<th>Types</th>
<th>Length, m</th>
<th>Characteristic Impedance, $\Omega$</th>
<th>Propagation velocity, m/\mu s</th>
<th>Characteristic Impedance, $\Omega$</th>
<th>Propagation velocity, m/\mu s</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB cable</td>
<td>12.3</td>
<td>19.1</td>
<td>193</td>
<td>17.2</td>
<td>190</td>
<td>0.005 Np/m</td>
</tr>
<tr>
<td>400 kV cable</td>
<td>952</td>
<td>25.0</td>
<td>175</td>
<td>24.3</td>
<td>173</td>
<td>0.11 Np/MHz km</td>
</tr>
</tbody>
</table>

Table 1: Characteristic impedance, propagation velocity (using (7) to account for helical screen), and attenuation of CB cable (Section 3) and 400 kV power cable (Section 10) up to 10 MHz

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The propagation velocity is 190 m/µs, 5% lower compared with the derived value from (2). The helical structure of the earth wire screen is responsible for the difference. According to [18, 19], the velocity can be corrected by a factor

$$F_H = 1 + \frac{1 - \left(\frac{r_1}{r_2}\right)^2}{2 \ln \left(\frac{r_2}{r_1}\right)} \left(\frac{2 \pi r_2}{l_1}\right)^2$$

(7)

which takes the lay length, that is, the longitudinal distance covering one turn of the helical wire screen ($l_1 = 0.3$ m), into account. Multiplying this correction factor with (2) gives a result equivalent to the measured value. In further analysis, the attenuation of the CB cable is neglected and for $v_{cb}$ a constant velocity of 190 m/µs is assumed. In Fig. 5, both the experimentally determined time-domain signal and the signal constructed from the model parameters are shown. All reflections are represented correctly both in time of occurrence and in amplitude. The model parameters are extracted from the first reflections on $a$ and $a'$, so that these reflections must match. All succeeding reflections are correctly represented as well and serve as model verification.

4 Analysis of CB box

The CB box is connected with all three CB cables. Similar pulses as for Section 3 are applied to the far end of one of the CB cables.

4.1 Estimation of CB box impedance

Propagated pulses through CB cable 1 reflect at the cable end $a'$ (Fig. 2b) from the impedance seen at $a'$. This load consists of a series connection between the characteristic impedances of CB cables 2 and 3 (two times $Z_{ccb}$) and the impedance of CB box ($Z_{cbbox}$). The impedance $Z_{cbbox}$ will be obtained by the reflection measurement. The loop inductance can be estimated by considering the copper bar connections inside the CB box as a circular loop [20], Fig. 6

$$L_{cb} \approx \mu_0 r_{loop} \left(\frac{8}{\pi r_{loop}} \ln \frac{r_{loop}}{r_{bars}} - 2\right), \quad r_{loop} >> r_{bars}$$

(8)

Here, $r_{loop}$ is the radius of the circular loop and $r_{bars}$ is half of width of the copper bars. The effective ‘radius’ $r_{loop}$ of the...
loop is found by approximating its ‘circumference’ with the sum over the individual bar lengths

\[ r_{\text{loop}} \approx \frac{1}{2\pi} \sum_{k=1}^{6} l_k \]  

(9)

With \( r_{\text{bars}} = 15 \text{ mm} \) and \( r_{\text{loop}} = 143 \text{ mm} \), a value of 420 nH is calculated.

### 4.2 Analysis \( Z_{\text{cbbox}} \)

The injected pulse (\( Y_{\text{inj}} \)) travels along the injection cable and is partly transmitted and partly reflected at \( a \). The transmitted fraction travels through the CB cable and reflects on the CB box connection \( a' \) (\( Y_{\text{bbox}} \)). The ends of CB cables \( b \) and \( c \) are open. The transfer function \( H_3 \) for reflected pulses on the CB box is

\[ H_3 = \frac{Y_{\text{bbox}}}{Y_{\text{inj}}} = H_{\text{inj}} T_{\text{cc}} T_{\text{cbox}} \alpha \exp(-2\gamma a/b) \]  

(10)

The reflection coefficient \( r_{\text{cbbox}} \) represents the reflection on CB box connection \( a' \) (Fig. 2b), and depends on \( Z_{\text{cbb}} \) and \( Z_{\text{bbox}} \)

\[ r_{\text{bbox}} = \frac{Z_{\text{cbb}} + Z_{\text{bbox}}}{3Z_{\text{cbb}} + Z_{\text{bbox}}} \]  

(11)

The only unknown parameter is \( Z_{\text{bbox}} \) from which the inductance can be derived

\[ Z_{\text{bbox}} = j\omega L_{\text{bbox}} \]  

(12)

In addition, pulses are injected in CB cable 2 while cable receiving ends \( a \) and \( c \) are open, likewise, in CB cable 3 while cable receiving ends \( a \) and \( b \) are open. The impedance \( Z_{\text{bbox}} \) is derived for individual pulse reflection measurements, which are done on each CB cable, applying (10)–(12). This gives \( Z_{\text{bbox}1}, Z_{\text{bbox}2} \) and \( Z_{\text{bbox}3} \), which are plotted in Fig. 7.

A drawback of the short CB cables is that only narrow windows in the time-domain signal could be selected from the recorded waveform to represent a specific feature (e.g. a direct reflection). By selecting a limited time window, lower-frequency content of the waveform is altered as the signal has not yet returned to zero completely. Therefore

**Table 2** CB box impedance from measurement and estimated value from CB box design

<table>
<thead>
<tr>
<th>( L_{\text{bbox}1} )</th>
<th>( L_{\text{bbox}2} )</th>
<th>( L_{\text{bbox}3} )</th>
<th>Average value</th>
<th>Estimate (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>443 nH</td>
<td>427 nH</td>
<td>430 nH</td>
<td>433 nH</td>
<td>420 nH</td>
</tr>
</tbody>
</table>

the transfer function calculated from the selected pulse is not accurate for lower frequencies. In this situation, information on the CB box impedance can only be obtained when its value substantially contributes to the impedance causing the reflections (11). As from a few MHz, the impedance by the CB box inductance becomes comparable with the CB cable characteristic impedance (19 \( \Omega \) from (1)), and its effect becomes visible in pulse reflection measurements. At 2 MHz the magnitude of \( Z_{\text{bbox}} \) is about 5 \( \Omega \), using the estimated value from (8). At lower frequencies, the CB box impedance has hardly any effect on the reflection coefficients. Omitting this range in the analysis, the impedance of the CB box shows inductive behaviour. The average over the three fitted values of 433 nH is close to the estimated value using (8), see Table 2. As motivated in Section 2, the frequency range of 2–10 MHz is most interesting for modelling the CB box for evaluating its effect on overvoltages, after the transient has travelled the distance from transition point to the first CB joint.

### 5 Model verification

The CB box inductance gained from measurements discussed in Section 4.2 is verified by applying the configuration depicted in Fig. 8. This analysis focuses on the transmission of injected pulses (\( Y_{\text{inj}} \)) at \( a \), which propagate through CB cable 1, CB box and CB cable 2. Subsequently, the pulses arrive at \( b \) where they are measured (\( Y_{\text{transm}} \)). The propagation path is represented by

\[ H_4 = \frac{Y_{\text{transm}}}{Y_{\text{inj}}} = H_{\text{inj}} T_{\text{cc}} T_{\text{cbox}} \alpha \exp(-2\gamma a/b) \]  

(13)

The transmission (\( T_{\text{bbox}} \)) from CB cable 1 to CB cable 2 is a product of the transmission coefficient at the end of CB cable 1 and the fraction that enters CB cable 2

\[ T_{\text{bbox}} = (1 + r_{\text{bbox}}) \frac{Z_{\text{cbb}}}{2Z_{\text{cbb}} + Z_{\text{bbox}}} \]  

(14)

The attenuation of coaxial measurement cable is neglected in transfer function (13) because its length is only 1 m.

**Fig. 7** Impedances of CB box obtained from pulse injection in three CB cables with the other ends open

**Fig. 8** Configuration for verifying the CB box model
The verification method compares an actual measurement with the simulation result. For the measurement, pulses are injected as illustrated in Fig. 8. Reflected and transmitted pulses are measured on positions a and b. In the simulation model, the signal at b is generated, based on the model parameters obtained in Section 4.2. Fig. 9 shows the measured signals at positions a and b, together with the simulated waveform at b. The transmitted experimental and simulated signals match both in amplitude and duration. Also the waveform is roughly represented when the inductance value of 433 nH, obtained from the measurements discussed in Section 4.2, is applied.

6 Simulation with lightning impulse

When the underground cable system is subjected to fast transients, like lightning strikes, the metallic earth conductors of the CB cable can be subjected to steep surge voltages. Surge arresters are placed at the earth screen of the CB cable for protection against overvoltages. For the CB cable used in the Randstad380 connection, 6.6 kV surge arresters are installed. To study the influence of the surge arrester on overvoltages, simulations are performed on the CB cable and box including the 6.6 kV surge arresters. Using the developed model for the CB cable and box, a simulation model is built in PSCAD. The applied model for the surge arrester is shown in the inset of Fig. 10. The values of the parameters $C_a$, $R_a$ and $L_a$ of the arrester are taken from [1]. The non-linear $V$-$I$ characteristic of the surge arrester, shown in Fig. 10, is implemented in the simulation model.

A 1.2/50 μs lightning surge voltage with 20 kV amplitude is applied to the CB cable and box in which the surge arrester is installed. This standard waveform is generally used for lightning impulse testing. To investigate the effect of the surge arresters on overvoltages, the simulation is performed on the system with and without arresters. The lightning impulse voltage is applied to the core conductor of one CB cable terminal, whereas the remaining two CB cables are left open. The voltages at the screen conductor of all three CB cables and the currents in the CB box are simulated. The results for simulated voltages at the screen conductor without and with arresters are shown in the plots of Fig. 11. The simulated voltages at three CB cable screens are indicated by $V_{sa}$. As it can be seen, without arresters the peak overvoltage is about 30 kV. With arresters, this voltage level reduces to about 16 kV. It is concluded that the presence of arrester results in a reduction of the overvoltage peak by almost 50%. The same simulation is performed for a 1.2/50 μs impulse voltage with 30 kV amplitude. The results are depicted in Table 3. $V_{cb}$ indicates the voltage between the CB cable core conductor and the screen. From these results, it can be observed that the strongest impact of the arresters is on $V_{cb3}$.

<table>
<thead>
<tr>
<th>$V_{sa1}$</th>
<th>$V_{sa2}$</th>
<th>$V_{sa3}$</th>
<th>$V_{cb1}$</th>
<th>$V_{cb2}$</th>
<th>$V_{cb3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>10</td>
<td>17</td>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>with surge arrester</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>17</td>
<td>43</td>
<td>30</td>
<td>15</td>
<td>33</td>
</tr>
<tr>
<td>without surge arrester</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 3 Simulation results of peak voltage level with 30 kV impulse voltage

Fig. 9 Experimental and simulated signals for the total measured record and zoomed in around 0.4 µs

Fig. 10 $V$-$I$ characteristic of 6.6 kV surge arrester; surge arrester model is shown in the inset

Fig. 11 Voltages at the screen of the CB cable without surge arrestors (left) and with surge arresters (right)
7 Conclusions

As part of the 400 kV underground cable system, the CB cable and the CB box is studied under fast transient conditions. A model for the CB cable and box has been developed, based on pulse injection measurements. Analysis of pulse injection measurements resulted in parameter values for the lumped parameters of the CB cable and box. The estimated inductivity of the CB box is quantitatively confirmed by the measurement. The model is used for performing simulations of the CB cable and box system to evaluate overvoltages occurring during lightning events. Furthermore, the influence of 6.6 kV surge arresters installed at the screen conductor of the CB cable is also investigated. From the simulation results, it is observed that the overvoltage peaks at the screen conductors are significantly reduced by the introduction of surge arresters.

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10 Appendix

The measurements of the propagation characteristics are performed as in [21] including the compensation of the effect caused by the adapter impedance $Z_L$ between measurement cable and 400 kV cable. Calibration of injection cable and adapter is required to compensate for their influence on injected pulse responses. The adapter should be installed in the field without jeopardising the power cable. Its dimensions are kept below 10 cm, so its effect can be modelled as a lumped component at least up to several tens of MHz. Calibration and measurement are conducted as follows:

- **Calibration injection cable** ($Z_{inj} = 50 \, \Omega$, length 50 m): The far end is short circuited (voltage reflection coefficient is $-1$).
  In the recorded signal, the injected and reflected pulses are separated into two waveforms from which their transfer function $H_{cal}$ is determined. $H_{inj}$ represents the transfer of a signal up and down the injection cable
  
  $$H_{inj} = -H_{cal}$$ (15)

- **Calibration adapter**: The short circuited adapter is connected to the injection cable. The transfer function $H_{cal}$ includes reflection $Y_A$ on a series impedance $Z_s$ representing the mainly inductive behaviour of the adapter; subsequently $Z_s$ can be calculated
  
  $$H_{cal} = \frac{Y_A}{Y_{inj}} = H_{inj} \frac{Z_s - Z_{inj}}{Z_s + Z_{inj}} \Rightarrow Z_s = Z_{inj} H_{inj} + H_{cal}$$ (16)

- **Measurement on cable**: The short circuit is removed and the transfer function between reflected signal $Y_{cable}$ and injected signal, the characteristic impedance of the cable is determined
  
  $$Z_{cable} = Z_{inj} H_{inj} + H_{cable} - Z_s \quad \text{with} \quad H_{cable} = \frac{Y_A}{Y_{inj}}$$ (17)

A pulse width of 100 ns is applied for injection in the 952 m long 400 kV cable section. This allows for accurate frequency response as from about 100 kHz (sufficient energy in signal) up to 10 MHz (the Fourier transform of the input signal is a sinc function with zero amplitude at 10 MHz). A value of
25 Ω is found for the characteristic impedance. The propagation velocity and attenuation characteristics are shown in Fig. 12. The propagation velocity ($\beta/\omega$) of 173 m/μs is lower than found for the CB cable, mainly because of the presence of the semi-conducting layers. Characteristic impedance and propagation velocity match the calculated values using (1), (2) applying (7) within 3 and 1%, respectively (Table 1, cable dimensions $r_1 = 28.2$ mm, $r_2 = 54.2$ mm and $l_1 = 0.70$ m). The effective relative dielectric permittivity [19], accounting for the effect by the semi-conducting layers (combined thickness is 3.5 mm), is taken 2.6.

A relation can be found for the accuracy of the cable impedance assuming that it is determined by the measured $H_{\text{cable}}$. For simplicity, the attenuation of measurement cable ($H_{\text{inj}} = 1$) and the adapter impedance ($Z_s = 0$) is neglected. With these approximations the reflection coefficient is equal to $H_{\text{cable}}$. The accuracy $\Delta Z_{\text{cable}}$ can be expressed as

$$\Delta Z_{\text{cable}} = \frac{2Z_{\text{inj}}}{(1 - H_{\text{cable}})} \Delta H_{\text{cable}}$$

$$\frac{\Delta Z_{\text{cable}}}{Z_{\text{cable}}} = \frac{2}{1 - H_{\text{cable}}} \frac{\Delta H_{\text{cable}}}{H_{\text{cable}}}$$

(18)

The accuracy of the cable characteristic impedance is highest when it is close to $Z_{\text{inj}}$ ($H_{\text{cable}} \approx 0$). Its relative uncertainty then is twice the relative uncertainty in $H_{\text{cable}}$, but increases fast when both characteristic impedances differ significantly ($H_{\text{cable}} \rightarrow 1$). Concerning the propagation velocity, its accuracy is basically determined by the distortion of the signal after travelling through the power cable. Estimates for accuracy in propagation velocity in single-core cables is typically of the order of 1% if sufficient signal energy enters the power cable ($H_{\text{cable}} \neq 0$) [19].

The measured attenuation ($\alpha$) is approximately linear with frequency with slope 0.11 Np km$^{-1}$ MHz$^{-1}$. Depending on the travelled distance, the maximum frequency of interest drops. Highest overvoltage is expected at the nearest CB joint, which is about 900 m from the overhead line to cable transition. Therefore frequencies exceeding 10 MHz are attenuated and are of less interest.

Fig. 12  Propagation velocity (top) and attenuation coefficient (bottom) of the 400 kV cable shown on the photo with adapter; the propagation velocity of the CB cable is shown as well