Transient modeling and sensitivity analysis of cable system parameters

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Abstract—Traditionally, Extra High Voltage (EHV) transmission systems consist exclusively of Overhead lines (OHL) but in the recent years the utilization of High Voltage AC (HVAC) underground power cables (UGC) is increasing due to environmental, political and operational aspects. The application of EHV cables will influence the operation of the transmission system in both steady and transient state. Therefore, formulation of accurate cable simulation models is of great importance in order to understand the new phenomena introduced. This paper presents a comparison between two cable models, a detailed and a more simplified one, as well as a sensitivity analysis on several cable parameters. In this way, guidelines can be extracted concerning the parameters that have larger impact on the cable response and must be modeled in detail and the ones where simplifications can be made for achieving better computational speed. The simulations are performed using software package PSCAD/EMTDC.

Index Terms—transient modeling, underground power cables, cable bonding, harmonic impedance, energization, PSCAD/EMTDC

I. INTRODUCTION

Recently, the Dutch transmission system operator, TenneT, extended the 380 kV grid with a new connection where underground power cables are integrated in order to guarantee sufficient electric power capacity for the densely populated Randstad region. Due to the limited experience in the Netherlands with underground power cables at 380 kV level, the Dutch TSO decided to research switching operations in HVAC cables, in order to identify possible undesired overvoltages and resonance phenomena. In order to study this kind of phenomena accurate simulation models should be built in software packages suitable for transient studies where the chosen modeling detail and parameters of the cable is of the utmost importance.

In this study the connection of interest is the OHL-Cable-OHL connection in Randstad380 Southring between substations Wateringen and Bleiswijk. The connection consists of 12 mutually coupled single-phase cables which are divided into 28 different cable segments with varying length and trench type. The 28 different cable segments are grouped into 12 minor sections, while three successive minor sections form one major section of approximately 2.7 km length. Within one major section, the minor sections are connected via cross-bonding joints, while the major sections are connected via a straight through joint [1], [2].

This is the actual cable configuration and the model is referred to as "detailed". To reduce the designing and simulation time, a simplified cable model has been developed. In this "simplified" model, all minor sections are assumed to have a single cable segment, instead of a group of segments, with 0.9 km length and the same open trench type. The main reason of such a simplification is that the minimum cable segment's length is the dominant parameter influencing the simulation time, since the software is based on traveling wave theory. Moreover, the fact that the system is very big (12 cables) and the cable length is very short can result in large passivity violations causing unstable simulations [3].

However, simplifications introduce inaccuracies that should be further investigated. For this purpose, the two cable models (detailed and simplified) are being compared using as criteria the frequency domain response (harmonic impedance) and the time domain response during energization transients. Moreover, the impact of several cable design parameters is investigated since parameter variation related to the cable type, configuration, and topology modify the transient behavior of the transmission line.

In Section II the detailed and simplified cable models developed in PSCAD/EMTDC are described. The comparison of the aforementioned models in both time and frequency domain is shown in Section III. In Section IV a sensitivity analysis on the cable system parameters is conducted. Section V gives the conclusions.

II. CABLE SYSTEM MODELING

The configuration of the mixed OHL-Cable transmission line is shown in Fig. 1. From substation Wateringen there is an 4.4 km OHL 1 which comprises a double circuit (white and black circuit) 380 kV and a double circuit 150 kV transmission lines. Then each phase of both circuits is connected to two parallel 10.8 km, 380 kV cables, to match the transport capacity of the overhead line. Finally a 6.8 km OHL 2 consisting of two 380 kV circuits extends from the cable transition point to substation Bleiswijk.

For the construction of the OHL and cable model in PSCAD/EMTDC the Frequency Dependent (FD) Phase model
was utilized. This model is regarded as one of the most accurate and stable models for overhead line or cable representation as it strives to represent the full frequency dependency of a transmission system and the resistance, inductance and capacitance of the line are represented using distributed parameters [3], [4]. However, for the construction of such a model information of the geometric and material properties of the line, pylon or cable trench and earth resistivity are needed.

A. Cable designing parameters

The actual cable consists of seven layers: core conductor, conductor screen, XLPE insulation, insulation screen, copper-wire screen, lead sheath and PE outer sheath. However, for this analysis the model adopted comprises of four equivalent layers: core conductor, XLPE insulation, screen and outer sheath. The detailed configuration and parameters of the OHLs and cable as well as the derivation of the equivalent layers can be found in [1], [2] and [5]. The cable design parameters are also shortly described below:

1) The actual core conductor consist of stranded copper wires but in PSCAD software only solid conductors can be modeled. Thus, by using a solid conductor in the model a corrected equivalent copper resistivity is adopted:

\[
\rho_C = \rho_{Cu} \frac{\pi r_C^2}{A_1}
\]

where \( r_C \) is the conductor radius and \( A_1 \) is the nominal area of the conductor.

2) The copper wires in the screen are translated into a solid copper tube whose thickness is chosen to have the same DC resistance. The outer radius of this equivalent layer is chosen to be equal to the inner radius of the lead sheath \( r_s \). This will change the equivalent radius of the insulation layer to:

\[
r_I = \sqrt{r_s^2 - \frac{A_2}{\pi}}
\]

where \( A_2 \) is the nominal area of copper wires in screen. Moreover, the copper wires of the screen are not straight along the cable but laid helical with \( N \) number of turns per meter. So a corrected equivalent permeability \( \mu_I \) of the equivalent insulation layer is calculated as:

\[
\mu_I = \mu_{XLPE} + \frac{\mu_{XLPE}}{\ln(r_1/r_C)} \cdot 2\pi^2 N^2 (r_I^2 - r_C^2)
\]

3) Since the modeling of semi-conducting layers is not possible in PSCAD, these layers are considered as part of the XLPE insulation and the corrected equivalent permittivity is:

\[
\varepsilon_I = \varepsilon_{XLPE} \frac{\ln(r_I/r_C)}{\ln(b/a)}
\]

where \( r_I \) is the radius over the insulation including the semi-conduction layers, \( b \) is the outer-radius of the insulation and \( a \) is the inner-radius.

B. Cable Configuration and simplifications

The cable length is 10.8 km and comprises 28 segments with different lengths and trench types (five types of open trench and two types of horizontal directional drilling). The different trench types are shown in Fig. 2.

![Diagram](image_url)

Fig. 1. Configuration of the OHL-Cable-OHL 380 kV connection between substations Wateringen and Bleiswijk.

![Diagram](image_url)

Fig. 2. Trench types: (a) two types of open trench (O1 and O3) and two types of horizontal directional drilling (b) H1 and (c) H2.

The segments are grouped into 12 minor sections. Within each minor section, two neighbouring segments are directly connected. Three minor sections are grouped to one major section. Within each major section, two neighbouring minor sections are connected via cable cross-bonding joints (see Fig 3). As proposed in [6], the impedance introduced by the cross-bonding is represented by a 1 \( \mu H \) inductance. Two major sections are connected via cable straight-through joint with impedance of 10 \( \mu H \).

In the "detailed" model all 28 segments with their different lengths and trench types are incorporated in the model. However, both the time to construct and to simulate such a
complicated model is excessive. That is because in order to obtain accurate results the simulation time step should be ten times less than the time a traveling wave needs to travel the shortest cable segment \[3\], \[7\]. Since the smallest segment is 100 m the simulation time step should be 0.05 \( \mu \text{s} \). Moreover, such a small cable length can cause instability problems due to large passivity violations. Instability problems was also encountered in this study and were solved by changing the curve-fitting parameters, neglecting the coupling between the two cable circuits and changing the length of the smallest segment from 100 m to 200 m.

However, this trial and error procedure is not practical and might not work for large cable systems. Thus, to avoid these kinds of problems a simplified model of the cable system is introduced where:

- All minor sections consist of only one segment (12 segments in total) with the same length (0.9 km).
- For each segment the same trench type was chosen (open trench with typical cable depth of 1.4 m).

### III. CABLE MODEL COMPARISON

In order to check whether the aforementioned simplifications produce inaccuracies when studying slow front transients in the mixed OHL-cable configuration of Fig. 1 a comparison between the configuration containing the detailed and simplified cable model is conducted in both frequency and time domain. In both cases the OHL model is the same.

#### A. Frequency domain comparison

In the frequency domain the harmonic impedances of the two models are compared. In this study the positive sequence harmonic impedances are calculated from Wateringen side, using the frequency scan component of PSCAD/EMTDC with a fixed step of 10 Hz and the frequencies of interest are up to 5 kHz. The lower frequency resonances are the most severe since they are weakly damped and sustained for longer time \[8\]–\[10\].

For the first comparison no external network was considered since it could “hide” possible inaccuracies due to its dominant inductance. Of great importance is the correct representation of the frequency and magnitude of the series and parallel resonant points.

As can be seen from Fig. 4 both the frequency and the magnitude of the first series resonance is similar in the two models, only the frequency is 20 Hz higher in the simplified model. In the first parallel resonance a more noticeable difference is present, since in the simplified model is 70 Hz shifted and less damped. For frequencies higher that 3 kHz there is not good agreement between the two models.

If short circuit impedances for the external network from Wateringen and Bleiswijk side are used as the ones shown in Table II then the dominant series and parallel resonances of the calculated harmonic impedance (Fig. 5) are almost identical. In this case as well the impedance of the simplified model start to deviate significantly from the detailed one after 3 kHz.

#### B. Time domain comparison

For the time domain comparison the voltage response upon a switching action is used to compare the two models. The configuration of the switching action is shown in Fig. 6 where the white circuit is energized from Wateringen side while the black circuit is in service. For the rest of the grid short circuit equivalent impedances were used which were calculated using the PowerFactory model of TenneT for the whole transmission system (Table III). For the energization the worst case scenario that would produce maximum overvoltages is chosen, which is when the busbar voltage at the switching substation reaches its positive peak.
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>( I_{ph,sc} ) (kA)</th>
<th>( L_{sc} ) (mH)</th>
<th>( R_{sc} ) (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wateringen</td>
<td>17.6° – 88°</td>
<td>39.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Bleiswijk</td>
<td>28.3° – 84°</td>
<td>24.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table I: Short-circuit equivalent impedance values

The voltage responses and their Fast Fourier Transform (FFT) at substation Wateringen and Bleiswijk are shown in Fig. 7 and Fig. 8 respectively. The duration 0 to 0.08 sec is needed for the simulation to evolve to steady-state. In both substations the maximum overvoltage of the detailed and simplified model does not deviate more than 0.82%. Regarding the harmonic content of the voltage response, in both substations the main harmonic of the detailed model is at 368 Hz and for the simplified is shifted at 373 Hz while the damping in the simplified model is slightly higher. A larger shift to higher frequencies of approximately 20 Hz is observed for the second harmonic peak of the simplified model (at 1120 Hz).

From the comparison between the detailed and simplified model in frequency domain it is obvious that the harmonic impedance of the cable is significantly different for frequencies higher than 3 kHz. However, from the time domain comparison it is found that the maximum overvoltage produced by both models is the same as well as the frequency content of the voltage waveform upon a switching action. Thus, for switching transient studies the simplified model can be utilized.

IV. Sensitivity analysis on cable system parameters

When modeling a cable system for slow front transient studies there are a lot of aspects that can affect the accuracy of the simulation results. These aspects are related to uncertainties in the cable designing parameters (provided by the manufacturer) or in the cable laying configuration. They can also be related to simplifications that need to be done due to software limitations or for simulation time reduction. The effect of various parameters is studied, using frequency scans, in order to conclude which of them are important and need to be accurately modeled. For the sensitivity study the simplified cable model is used since the interest is mostly in the behavior of the resonance frequencies and not on their actual values.

A. Cable designing parameters

In this category the effect of a change in conductor radius, insulation thickness and number of turns in the metallic screen are shown. When one parameter is changed (e.g. conductor radius), other parameters are assumed constant (e.g. thickness of the other layers such as main insulation, metallic screen, outer sheath etc.).
It can be seen from Fig. 9 that the radius of the conductor greatly affects the harmonic impedance. Larger conductor results in higher cable inductance and thus the resonance frequencies are shifted to lower values.

Fig. 10 depicts that even a small change in the insulation thickness has a strong effect on the harmonic impedance where the first series resonance is shifted by approximately 40 Hz to lower frequencies when the thickness decreases because the capacitance of the cable increases.

As can be seen in Fig. 11 an increase in the number of turns results in a decrease in the resonance frequencies. That is because by increasing the distance the mutual impedance between the cables, \( Z_m \), decreases and for a cross-bonded cable an increase in the mutual impedance causes a decrease in the total positive sequence impedance.

Different inductances at the cross-bonding and straight-through joints result in insignificant changes in the harmonic impedance and can even be neglected when the frequencies of interest are limited to several kHz, see Fig 13.

A very long cross-bonded cable would have a large number of major sections. When simulating such a cable system, as the number of major sections increases, the simulation time greatly increases and in many cases a reduced number of major sections is used. However, as can be seen in Fig. 14 changing the amount of major sections greatly affects the harmonic impedance. Smaller number of sections results in greater asymmetry in the system while larger amount of sections is closer to the ideal cross-bonding (infinite amount of major sections) where perfect balancing is present.

For the simplified model all minor sections were chosen to have the same length of 0.9 km and a total length of 2.7 km for the major sections. However, in reality the length of the minor sections may differ, but this difference is most of the times small to keep the system as balanced as possible. Thus,
the lengths of the three minor sections are changed to 800 m, 900 m and 1 km. The total length of the major section is kept constant. In Fig. 15, the positive sequence impedances are shown when this length unbalance is present in one, two, three or four major sections. It is obvious that this change does not affect the harmonic impedance.

V. CONCLUSIONS

This paper investigates the impact of simplifications in cable system modeling both in frequency and time domain as well as the impact of uncertainties in cable designing parameters and laying configurations.

From the comparison between the detailed and simplified model it was concluded that both models are similar for frequencies up to 3 kHz while for higher frequencies both the impedance magnitude and the harmonic frequencies deviate significantly. Moreover, the switching action response in both models gives the same maximum overvoltage and the harmonic content of the energization voltage is similar, although there is higher damping in the detailed model.

From the sensitivity analysis it was concluded that from the cable designing parameters, uncertainties in the conductor radius and insulation thickness could result in considerable difference in the system harmonic impedance and a representation as accurate as possible is needed. From the sensitivity on the cable laying the most important aspects are related to the cable trench type and the amount of major sections.

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