Partial discharge propagation in high voltage XLPE insulated cables – measurement vs. modelling

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ABSTRACT
The goal of this study is to develop a numerical tool that would allow for prediction of certain characteristics of high voltage (HV) cables necessary for commissioning testing. These characteristics describe both: power frequency and high frequency PD performance. This document summarizes the results of the measurement of PD pulse propagation in a high voltage 230 kV cable and an attempt to model the propagation of such pulse using FEM. The results of the simulations show attenuation of the HV cable which is in agreement with the results of the measurement and the results previously published.

KEYWORDS
High voltage, extra high voltage, HV cable, EHV cable, partial discharge, PD, propagation, attenuation, modelling, commissioning.

INTRODUCTION
Underground and subsea high voltage (HV) and extra HV (EHV) cables are optimized to carry load at high voltage and, as opposed to the concentric telecommunication cables, they are not optimized for high frequency (HF) or radio frequency (RF) signals (1), (2), (3), (4), (5). However, during commissioning (after installation) testing, the cables should be subjected to a high voltage test for 60 minutes (6), (7), (8), (9) which is often combined with partial discharge (PD) measurement. PD are electrical pulses (1), (2), (3), (4), (10), (12), (13), (14) that occur either in the impurities of the insulation or at the interfaces where the geometry of the insulation changes. These “sparks” or PD result in small magnitude current pulses that have very high frequency content (1), (2), (3), (4), (5), (10), (12), (15) (16) (17), (18), and since the HV/EHV cables are not designed to carry these signals, there are natural constraints that have to be taken into consideration when PD measurement is to be performed.

There are various methods of detecting PD in high voltage cables (10), (12), (19), but if the distance from the PD source to the sensor is long, the PD measurement may be lacking the sensitivity (regardless of the sensor and method applied). The phenomenon of pulse propagation in HV cables is well researched, but the question: “how far from the source can a PD signal be detected?” still remains unanswered. Unfortunately, this cannot be answered easily answered, as it depends on several factors.

HF SIGNALS IN POWER CABLES
PD are electrical pulses (1), (2), (3), (4), (10), (12) and as a results, they have high frequency content and are subject to the same rules as HF signals used in telecommunication cables. Considering the fact that the wavelength of these high frequency pulses is much lower than the length of most of the HV cables, the PD propagation can be described by application of the telegrapher’s equations. Although this principle applies to both telecommunication and power cables, the difference between one and the other is in the dimensions and the design of the carrier – the power cables are not optimized for high frequency signal propagation because they have semi-conductive layers (semicon) which are absent in telecommunication cables. These semicon layers have very high permittivity and relatively low resistivity (3) and these characteristics contribute to the attenuation of HF signals at much higher degree than the XLPE insulation (2), (3), (16), (19), (18).

Another difference between telecommunication cables and HV/EHV cables is that HV/EHV land cables can only be shipped and installed in limited and shorter lengths which then have to be jointed together after installation/pulling. In extreme cases the number of joints on each phase on HV/EHV cables may exceed 30. These joints usually have bigger diameters and different materials than the cables and because dimensions and permittivity of material affect the surge impedance, the impedance of the joints is often different than that of the cables. For HF signals this means reflections and further attenuation.

The weakest links in the entire HV/EHV cable installations are the joints (10). Therefore, the commissioning testing efforts are focused on exposing defects in cable accessories (joints and terminations) and when the PD measurement is included, all accessories should be monitored during the test. When PD sensors are installed near or on the accessories, they are close to the potential PD source which increases the probability of detecting a defect if such occurs (10).

MEASUREMENT OF PD PULSE PROPAGATION IN 230 KV XLPE CABLE
A large amount of research on PD pulse propagation has been done on medium voltage (MV) cables (2), (3), (14), (19). When comparing HV/EHV with MV cables, the latter are less expensive, easily available, easy to handle and share concentric geometry with the HV cables. There is also a difference in length, presence and number of joints, as MV cables are usually much shorter and have fewer joints. Nevertheless, there has also been research on high voltage cables that show the attenuation in the 230 kV XLPE cable. The cable under test (CUT) consists of approximately 280 m of 230 kV rated (Um=245 kV) XLPE cable with 500 mm2 aluminum conductor and aluminum concentric neutrals as presented in Figure 1. The insulation thickness is 20 mm, the semi-conductive conductor screen is 0.5 mm while the insulation shield is 1 mm thick. The cable was on a steel...
The cable ends were cut straight to provide means to install an adapter to match the cable impedance to the source. The adapter allows for a clean injection of the pulse into the cable, thus preserving the shape of the pulse.

A close-up view of the adapter can be seen in Figure 2. After preparation of both ends of the CUT, a pulse generator was connected to one end along with a 4-channel oscilloscope to monitor the injection end and the remote end. Connecting the oscilloscope probes directly to the cable conductor allowed for recording the pulse without sensitivity loss due to the use of PD sensors.

A summary of the measurements is presented in Figure 3 and Figure 4. From the first plot one can read the following parameters:

- The injected pulse: peak 7.755 V at 2.80 ns
- The reflected pulse: peak 0.118 V at 3.267 µs

Considering the parameters from the plots, the time span between the injected pulse and the reflected pulse is 3.264 µs and the resulting propagation speed is 171 m/µs. The pulse measured at the remote end of the cable should be in the middle between the injected and the reflected pulse. From the plot in Figure 4, one can see that the peak of 2.482 V occurs at 1.632 µs which is exactly half of the aforementioned 3.264 µs time span.
pulse proves that the match was not perfect. On the other hand, this allowed for detection and verification of the measurement. The calculated attenuation of the pulse that travelled one way, on the basis of the measurement, is approximately -10 dB. In addition to the attenuation, there is also dispersion which is responsible for shape change of the PD pulse. This is clearly visible in the plots presenting the pulse in the time domain, but is even more pronounced in the plots of the FFT of the signal. Dispersion, as a frequency dependent attenuation is also clearly visible in the time domain and FFT plots (Figure 3 and Figure 4).

MODELING OF PULSE PROPAGATION IN A 230 KV CABLE

An empirical experiment is a great source of information but the limitation of the measurement is obvious – it is feasible within limited scope and changing the scope is usually expensive and time consuming. If one can build a model of the phenomena of interest and can verify the results of calculations with the measurement, then the calculations for different materials or different configurations are relatively easy. Simulations, however, have their limitations and the results have to be carefully reviewed. The more sophisticated the problems, the more sophisticated the models become. The calculations become more difficult and there is higher probability of error. In any case, a good model is as good as the input data, which is one of the most common problems of many researchers because there is always limited information on material properties. This however, can somehow be mitigated by sensitivity studies or estimated values.

In this study, the author wanted to build a model that would be a good starting point for further work on this subject. In order to avoid errors in the early stage, the modelling process was started from the easiest model that is gradually improved to obtain a model that represents reality as best as possible. Previous research was helpful in this process [15], [17], [18], [20].

Modelling choices

The author chose finite element method (FEM) as opposed to analytical methods used in electromagnetic transient programs. Both methods have their pros and cons and the preference to use FEM comes from the flexibility FEM that allows for solving non-standard cases at greater accuracy. The drawback of FEM is complexity and a more time-consuming process of modelling and solving the problems.

Modelling steps

While attempting to build a model using FEM, the following questions have to be answered:

- What physics does the problem involve?
  - In this case, the physics involved is the electromagnetic field described by the Maxwell equations.
- How many dimensions are needed? Is there any symmetry that would allow for simplification of the model?
  - A cable can be modelled in 3D, but the model may be huge and difficult to solve.
  - A 2D axisymmetric geometry takes advantage of the concentricity of the cable and the fact that the geometry can be drawn by simply revolving a 2-dimensional surface. This would result in a much smaller model that could be solved much faster. Therefore this is the method of choice.
  - Any lower order of geometry would lack certain information that would render the model incorrect.
- What are the dimensions of the model?
  - Cable length should not exceed 20 m due to the size of the model when both semi-conductive layers are present.
  - Cable insulation radial dimensions are those of the 230 kV cable.
- Is the mesh manageable? If the number of elements exceed 100,000, more computer resources may be needed and the time to obtain a solution may increase.
- What are the governing equations?
  - Maxwell equations for electro-magnetic field:
    \[ \nabla \times \mu_r^{-1} (\nabla \times \mathbf{A}) + \mu_0 \sigma \frac{\partial \mathbf{A}}{\partial t} + \mu_0 \mu_r \left( \frac{\partial \mathbf{E}}{\partial t} \right) = 0 \]  \[ [1] \]
  - All material properties available?
    - XLPE:
      - relative permittivity=2.3,
      - relative permeability=1,
      - conductivity=10^{-15} S/m
    - Semicon [3]:
      - relative permittivity=200,
      - relative permeability=1,
      - conductivity=1.0 S/m
- What are the boundary conditions?
  - Test end of the cable: matched source that injects a pulse (Figure 5):
    \[ Z = \frac{V}{I} \]  \[ [2] \]
  - Remote end of the cable: either matched impedance, open end or shorted end. The results presented below are for matched impedance:
    \[ Z = \frac{V}{I} \]  \[ [3] \]
  - Shield and main conductor modelled as perfect conductors:
    \[ \mathbf{n} \times \mathbf{E} = 0 \]  \[ [4] \]
- What kind of study?
  - In order to solve travelling waves problem, one needs to choose a time dependent solver. Frequency domain or stationary solvers are not suitable for this task.

Results

The process of building and solving the model consisted of multiple steps. The solutions; however, were checked against known cases as follows:

- First a simple model of a cable (Figure 6) was developed with only one domain consisting of air insulation. Since the relative permittivity and permeability of air is approximately 1, the propagation
speed in air should be equal to the speed of light.

○ Result: The propagation speed was verified to be the speed of light and no attenuation was observed. For the cable length of 20 m the time difference between peaks (Figure 7) is 134 ns which yields the propagation speed of 298.5 m/µs.

Figure 6 Geometry of the cable with air or XLPE insulation

Figure 7 The results of simulations: air insulation only

- The second step was to change the insulation from air to XLPE without the semicon layers. In order to achieve this, the permittivity was changed to 2.3 and the conductivity to \(10^{-15}\) S/m. The result of this calculation should be that the propagation speed is lower by square root of the permittivity, i.e. \(\sqrt{2.3}=1.517\).

○ Result: The obtained propagation speed is 198 m/µs which is in line with the theoretical value (\(\sqrt{2.3}=1.517\) times lower than the speed of light). The result is presented in Figure 8.

Figure 8 The results of simulations: XLPE insulation without semi-conductive shield

- The third step of the modelling was to add semi-conductive insulation screen (Figure 9). The 1 mm thick screen of permittivity 200 and conductivity 1 S/m [3] was added on the surface of the insulation.

○ Result: the propagation speed decreased slightly (Figure 9). The magnitude of the injected and reflected pulse changed as well.

Figure 9 Geometry of the cable with XLPE insulation and insulation screen

Figure 10 The result of simulations: XLPE insulation with semi-conductive insulation screen

- The subsequent step was to add semi-conductive conductor screen of the same properties as the insulation shield and the thickness of 0.5 mm.

○ Result: the propagation speed further decreased (Figure 12). The magnitude of the injected and reflected pulse decreased as well. The trend is correct.

Figure 11 Geometry of the cable with XLPE insulation, conductor shield and insulation screen
The provided examples of the FEM modelling are the first step in building a generic model of HV cables. When two semi-conductive shields are added it means that in a long piece of cable (20 m in this case) two thin layers (0.5 mm and 1 mm) are added and require sufficiently dense mesh to obtain an accurate solution. This means that the model becomes very large and the time and resources needed to solve the model increase drastically.

The plots presented in Figure 7, Figure 8, and Figure 10 look very similar and the differences can only be noticed after careful investigation. It is much easier to compare numerical values, thus propagation speed and attenuation were calculated for each plot. The summary is presented in Table 1 below.

### Table 1 Summary of the simulations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Propagation speed [m/µs]</th>
<th>Attenuation [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air insulation</td>
<td>299</td>
<td>0</td>
</tr>
<tr>
<td>XLPE</td>
<td>198</td>
<td>-12.2</td>
</tr>
<tr>
<td>XLPE with insulation screen</td>
<td>194</td>
<td>-12.5</td>
</tr>
<tr>
<td>XLPE with conductor shield and insulation screen</td>
<td>194</td>
<td>-13.0</td>
</tr>
<tr>
<td>CUT (measurement)</td>
<td>171</td>
<td>-9.9</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

The study is based on the author’s HV/EHV cable field testing experience and the goal is to develop a universal FEM model that could be used in preparation for future HV commissioning tests. In this document only the HF component of the model is presented.

The results of the calculations presented in this study show that the semi-conductive screens change the characteristic of the cable as expected. In the results of the FEM model the following phenomena can be observed:

- High permittivity of the semi-conductive layers decreases the propagation speed (velocity factor),
- High permittivity of the semi-conductive layers increases attenuation and dispersion of the HF signals,
- The behaviour of the model reflects the measurement although the magnitudes are different which is most likely caused by the wrong parameters.

It is interesting to notice that one semicon layer decreases the propagation speed while the second layer has almost no further impact. However, the second layer increases the attenuation at a much higher rate than the first layer.

The model is not perfect and is limited in the following areas:

- The model does not take into consideration the HF performance of the conductor (skin effect),
- The actual parameters of the semi-conductive material in the CUT are not known and were based on [3],
- The dispersion of the cable is not clearly visible.

The author plans to continue working on this topic by filling the gaps, i.e. include the actual conductors and characterize the material of the semicon from the CUT.

The author is also planning to study the impact of the semicon material properties and its thickness on the performance of the cable.

### Acknowledgments

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### References


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[9] IEC 62067 Power cables with extruded insulation and their accessories for rated voltages above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) – Test methods and requirements, 2011.


GLOSSARY

FEM: Finite Element Method
EHV: Extra High Voltage
HV: High Voltage
MV: Medium Voltage
HF: High Frequency
RF: Radio Frequency
PD: Partial Discharge
CUT: Cable Under Test
Semicon: Semi-conductive layer