

## MEASURING PD PROPAGATION IN COMPLEX MV DISTRIBUTION NETWORK CONFIGURATIONS

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### ABSTRACT

*The presence of Partial Discharge (PD) activity in an electrical network indicates potential future failures that could be prevented knowing the PD source location. Although several location techniques are used, the accurate location in complex configurations is a difficult task because the PD pulse is attenuated, dispersed and reflected according to the cable system configuration. The pulse shape is also distorted and measurements are influenced by high amplitude noise and other external interference. This paper investigates the behaviour of PD pulses propagation in a laboratory controlled medium voltage network that allows reconfiguration and repeatability under the same conditions. An online PD monitoring system is used to register the PD activity and a time-of-flight (TOF) method is applied to determine the time of arrival of pulses at different points of this network. The pulse propagation velocity is subsequently calculated. The main objective is to determine if the presence of different components, like transformers, switchgears, substations, busbars, etc. significantly affects propagation. An average propagation velocity throughout the cable system will be calculated. It will be determined if this value is useful in determining PD source location and its relative error.*

### INTRODUCTION

On-line partial discharge condition monitoring of distribution networks is a diagnostic tool that has increased in use over the last decade. PD activity itself is only a symptom of an existing discharging defect source, and can be used as an early warning of future breakdown. Although the PD magnitude is an important feature, more interesting is the evolution over time. To evaluate this, measurements must be repeated several times, and always in the same conditions, which, in the field, is difficult when we have many factors that change in the network, for example, load and voltage fluctuations, environmental conditions, etc. The interpretation of the results is often also something that needs experience.

Nowadays, there is interest in smart diagnostic solutions in the grid using permanent monitoring systems, but these measurements have their own uncertainty problems possibly being influenced by: signal harmonics; interharmonics; power line communication; noise; temperature effects; phase jumps, and phase imbalance, even if we are not measuring them directly. They are almost always present in real grids at some level, often at the same time, and are themselves time varying.

In order to learn and gain experience in PD measurements in MV distribution networks, practical experimentation in a Smart Grid laboratory (UDEX laboratory at Ormazabal) has been performed over the last years to build up a database of known defect types commonly found in distribution networks [1]. More precisely, defects in substations with which we can optimize and apply different intelligent algorithms for the detection and identification of PD sources in “real-life” situations.

### PD PROPAGATION BACKGROUND

The propagation of partial discharge pulses in cables is considered as a traveling wave problem due to the few nanosecond duration of the pulse. The pulse will be attenuated, dispersed and reflected according to the cable system configuration. To analyse these phenomena, the cable could be modelled as a transmission line, which is characterized by two parameters: the characteristic impedance  $Z_c$  and the propagation coefficient  $\gamma$ . In equation (1) the analytical model of the propagation is shown. It includes the attenuation coefficient  $\alpha$  and the propagation velocity  $v_p (= \omega/\beta)$ .

$$\gamma = \alpha + j\beta = \sqrt{ZY} = \sqrt{(r + j\omega)(g + j\omega c)} \quad (1)$$

Cable structure, geometry and characteristics have to be known to calculate the theoretical propagation. However, in practice, some of these data are not available and laboratory testing has to be done. This represents an issue when cables must remain in service and online measurement has to be carried out.

The main goal to calculate the propagation velocity in cables is to detect the PD source location. An alternative to the analytical model is the time-of-flight (TOF) method. From the PD source, the pulse will split and propagate in both directions; each pulse can be measured at each cable end if a two-sided measurement system is installed [2]. The difference in the time of arrival (TOA) is defined as:

$$\Delta t_{oa} = t_{oa2} - t_{oa1} \quad (2)$$

If the total cable length  $l_c$  and the location of a theoretical PD source  $x_{PD}$  are known, the velocity propagation could be estimated as:

$$v_{cp} = \frac{2(l_c - x_{PD})}{\Delta t_{oa}} \quad (3)$$

If the cable has different sections, the velocity obtained is the weighted average velocity  $\bar{v}_{cp}$  of the total cable-connection. Moreover, the measurement units, in both cable ends, must be well aligned to measure  $\Delta t_{oa}$ . Some synchronization techniques are: Stable independent clocks, Global positioning system (GPS), Pulse injection [2].

An on-line measurement technique implies that the cable remains in service. Therefore, the medium cable system starts from the high voltage substation and ends in the low voltage transformer, with RMUs, switchgears or other substations in between. The sensors installed in this system will detect the PD signal shape distorted, due to the systems components, and also noise and interference signals from the grid. Hence, to determine the TOA, some algorithms exist regarding these issues, for example: trigger level, signal energy, Gabor centroid, phase in frequency domain, etc. [3]. The trigger level method or threshold detection was proposed for [4]. The  $t_{oa}$  is recorded at the time at which the PD signal exceeds a certain threshold level that is chosen by the user according to the noise level.

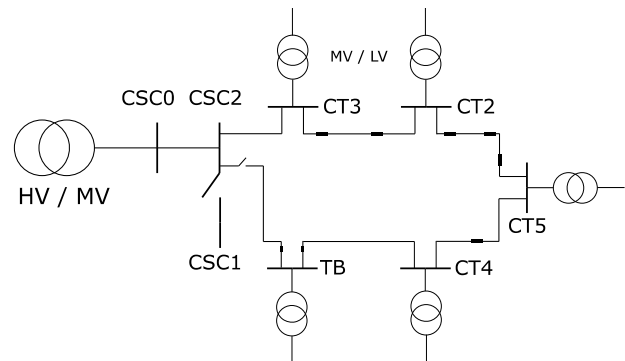
On the other hand, attenuation constant, real part of  $\gamma$  in equation (1) is frequency dependent and higher frequencies attenuate faster while propagating in the cable. Methods to estimate this constant were investigated in [5]. Finally, the pulse will be also reflected and refracted on its travel path due to other cable system components and their associated impedance changes. These quantities can be estimated by the reflection and transmission coefficients [3].

The main objective of this work is to calculate velocity propagation and attenuation in a complex MV cable system, the experimental details are explained in next section.

## EXPERIMENTAL SETUP

A real MV grid installation is used to perform the practical on-line PD measurements, this is a part of a highly configurable medium voltage laboratory called UDEX [6]. As shown in Figure 1, it consists of a main busbar (CSC2) feeding 5 different MV/LV substations; CT2, CT3, CT4, CT5 and TB, that are all connected through underground cables. The main cable installed in this system is a single phase 18/30 kV EPR cable with

aluminium conductors and a metallic copper wire screen, from two different manufacturers and interconnected by junctions. In addition, 16 meters of XLPE cables exists in the installation. The substations are equipped with switchgear compartments, which connect cables and transformers to a common busbar.



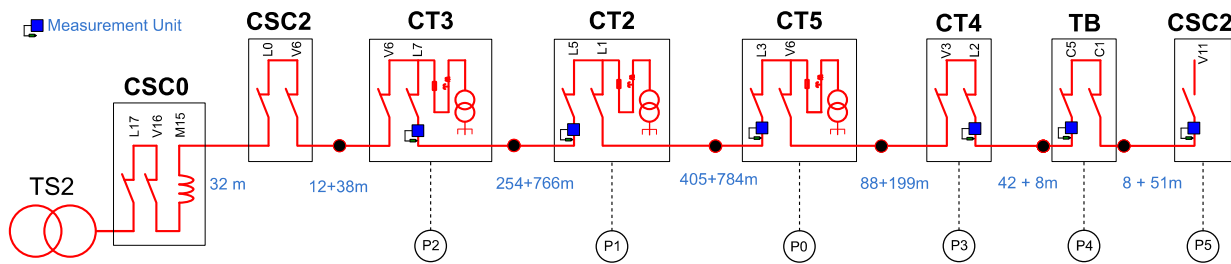
**Figure 1:** Experimental MV network.

Capacitive sensors are installed directly into the T-junction cable end-plug within the switchgear enclosure in each substation, allowing a two-sided measurement system.

The first stage of this work consists in injecting a reference pulse inductively in one single-phase cable, and detect this signal in other substations at the same time, through the PD monitoring system that is synchronized by GPS. The time of arrival is measured in each substation and, knowing the cable length installation, the propagation velocity is calculated by Eq. (3). The power spectra density of each signal is also registered to determine the attenuation. Then, a real PD source is placed in the same point and, following the same procedure as before, the signals are registered and compared to the reference.

In Figure 2, a more detailed scheme of the cable system under test is shown. Each substation is represented as switchgear; with the incoming and outgoing cables, the connection with the transformer and the common busbar. The cables junctions are represented with black dots in the cable length. As the cables are already installed underground, their lengths were approximately measured with the architect plan of the installation. The measurement units, where the signals are detected, are also highlighted.

The case studies will be explained in detail in the next section, with the results and discussion for each.



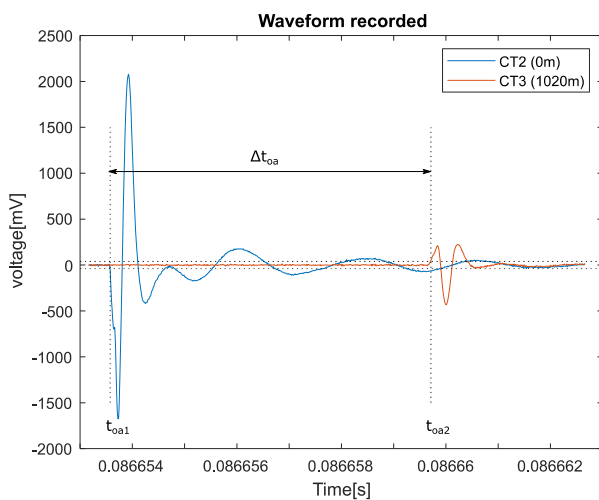
**Figure 2:** Scheme of the cable system under test

## RESULTS AND DISCUSSION

### Case 1

In this case, in order to analyse the propagation only in the cable, a pulse is inductively injected in CT2 (point P1) and measured at both ends of this cable of approximately 1020m. For this purpose both switchgears are opened (CT3<sub>L7</sub>-CT2<sub>L5</sub> respectively) to isolate this cable from the grid.

The time of arrival of each signal is recorded by the measurement units, and applying the trigger level method,  $\Delta t_{oa}$  is estimated. The values registered are listed in Table 1 and waveforms of the detected signals are shown in Figure 3.



**Figure 3:** Waveform recorded in two different substations.

**Table 1:** Values recorded from measurement units.

Substation	CT3	CT2
Propagation Distance (m)	1020	0
Propagation times (us)	6,138	0
Max abs. Voltage (mV)	2077,9	211,1
Pulse polarity	Positive	Negative

The velocity propagation is obtained from equation (3) and the absolute voltage attenuation is calculated as:  $(V1 - V2)/distance$ . The results are listed in Table 2. After several tests, with different measurements units,

even a commercial oscilloscope, we can conclude that the average velocity in this type of cable is approximately  $166 \pm 1$  (m/us).

**Table 2:** Estimated velocity and Attenuation in a single cable.

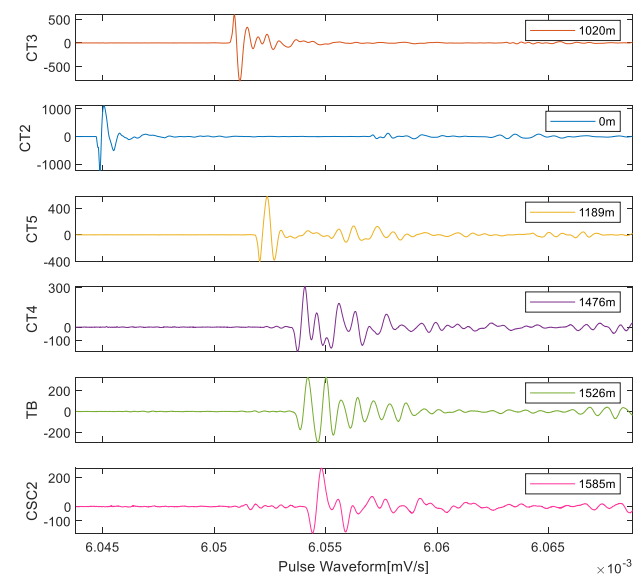
Section	CT3-CT2
Type	Cable open ended
Velocity (m/us)	166,18
Attenuation Abs (mV/m)	1,83

### Case 2

To test if the velocity is constant in all sections of this circuit, a pulse will be injected in CT2 and then in CT5. The network will be energized to a few kilovolts. The pulse will be recorded at other points (P<sub>0-5</sub>) of the circuit, as indicated in Figure 2.

#### Case 2.1: Injection in CT2

Pulse is inductively injected in CT2, downstream from the measurement unit. The recorded pulse waveform with capacitive sensors in all substations is shown in Figure 4.



**Figure 4:** Waveform recorded in different substations. Injected pulse in CT2.

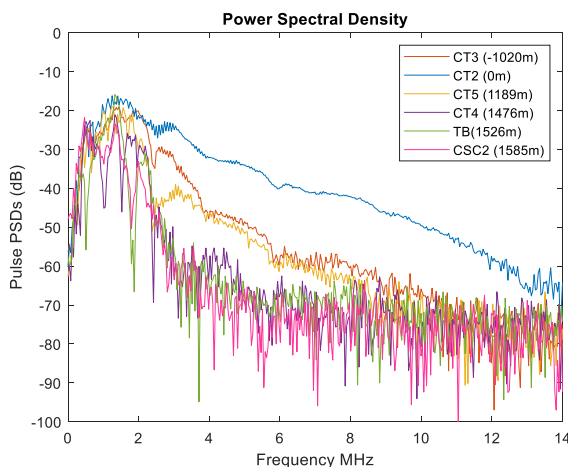
It can be seen that the pulse clearly propagates in two directions; in CT3 a positive pulse was recorded meanwhile in the other, the polarity is negative. The voltage attenuation with distance is also shown. As in the previous case, times of arrival are registered and the velocity estimated for each section. Several measurements were made with the same synchronised measurement unit, but at every recorded timestamp different results were found, with a standard deviation up to 24m/us. Results from a measurement set with the lowest standard deviation are listed in Table 3. It was expected to measure the same velocity as in the previous case in section CT2-CT3 but results differ.

**Table 3:** Estimated Velocity and Attenuation of injected pulse in each section of the circuit.

Section	Type	Velocity (m/us)	Attenuation (mV/ m)
CT2-CT3 1020m	Cable	169.295	0.629
CT2-CT5 1189m	Cable + Busbar x1	165.426	0.702
CT2-CT4 1476m	Cable + Busbar x3	166.076	0.715
CT2-TB 1526m	Cable + Busbar x3	169.556	0.698
CT2- CSC2 1585m	Cable + Busbar x4	166.404	0.665

With these values, average velocity in the entire network is calculated as 167 m/us. If this average value is assumed, the error in find the PD source is 2% in the worst case. The voltage attenuation remains almost constant in all sections.

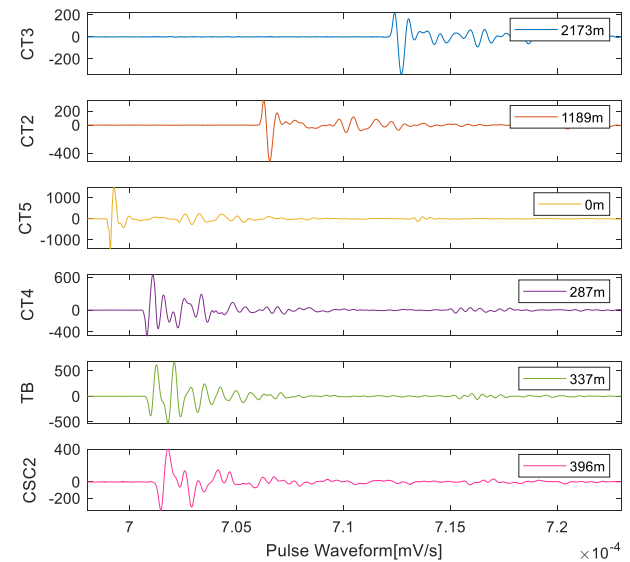
The power spectral density is also represented in Figure 4. It can be seen how higher frequencies are attenuated for longer distances. The PSD is also affected by the injection and measurement sensors.



**Figure 5:** Power spectral density of pulses registered in each section of the circuit.

### Case 2.2: Injection in CT5

To compare with the previous results, the injection point is changed to CT5, and once again the propagated pulse is registered in the other substations. The respective pulse waveforms are shown in Figure 6. The pulse polarities are according to the injection point, positive in CT2 and CT3, and negative in the other ones. In this case, the average velocity calculated was 170 m/us.



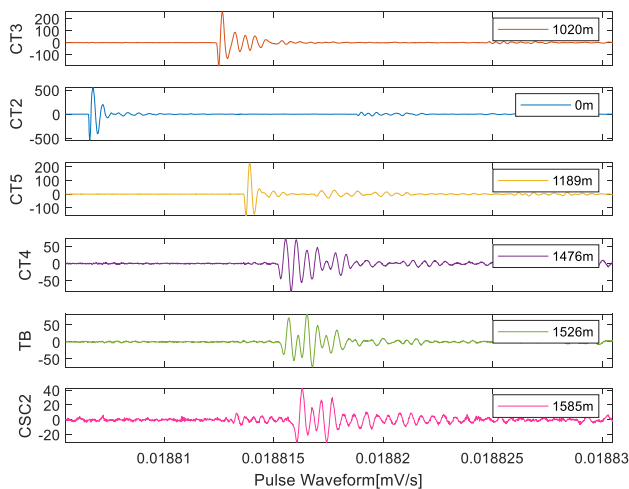
**Figure 6:** Waveform recorded in different substations. Injected pulse in CT5.

The aim of these measurements was to have a reference to the theoretical PD propagation through the circuit from a known injected reference signal. In the next case, a real PD source is recreated in CT2.

### Case 3

A real PD source is produced next to the transformer in CT2. The network is energized to 32 kV. The pulse waveform registered in each substation is shown in Figure 7, the pulse polarity are all the same; negative. The reason could be because the PD pulse is induced in the busbar in CT2 and then propagated into the circuit.

The estimated velocity and attenuation for each section are listed in Table 4. Different results were found for each section compared to the previous case, and no common factor was found between them. However, the average velocity calculated was 170 m/us as before. Otherwise, the voltage attenuation decreases by 50%, but still remains almost constant in all sections. It has to be highlighted that the PD location is not exactly in the same point as the injection point as the previous case.

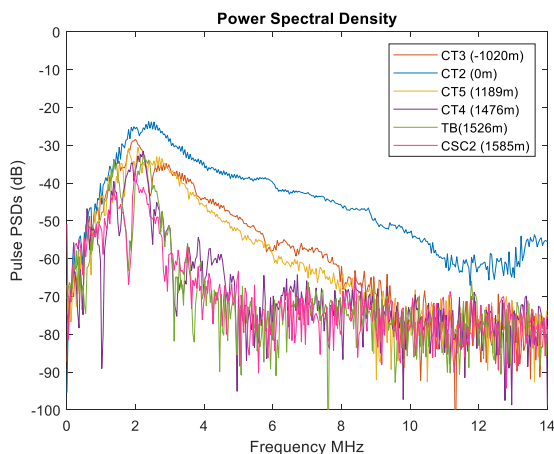


**Figure 7:** PD pulse waveform registered in different substations. PD source in CT2.

**Table 4:** Estimated Velocity and Attenuation of PD pulse in each section of the circuit.

Section	Type	Velocity (m/us)	Attenuation (mV/ m)
CT2-CT3 1020m	Cable	173.987	0.339
CT2-CT5 1189m	Cable + Busbar x1	167.170	0.320
CT2-CT4 1476m	Cable + Busbar x3	169.315	0.335
CT2-TB 1526m	Cable + Busbar x3	172.186	0.329
CT2- CSC2 1585m	Cable + Busbar x4	166.842	0.321

The power spectral density for this case is shown in Figure 8.



**Figure 8:** Power Spectral Density of PD pulses in different substations.

## CONCLUSIONS

In this paper, results from practical PD measurements in a complex MV network were presented. Pulse velocity and voltage attenuation were calculated in different cable systems with a TOF method. It has been shown that the voltage attenuation depends on the pulse type and location more than the components of the circuit, otherwise if we assume an average velocity for all the circuit, error in PD location could be up to 2%, which is acceptable for a first approximation.

Significant variability was observed in time of arrival results. Clock skew between the independent high frequency measurement units was a factor not taken into account in this work. Future work will concentrate on improving these measurements to determine if the quantity of busbar, switchgear and other components affects the pulse propagation in each section.

## Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 676042

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