Advanced technique for partial discharge detection and analysis in power cables

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Abstract
Polymeric cables are the most common choice for transmission and distribution in populated areas, as well as for the connection of components (transformers, GIS, etc.) in new power stations, replacing paper-oil cables. Indeed, they do possess superior characteristics with respect to oil-filled cables. As an example, they do require lower maintenance, they are lighter (easier to deploy) and, in case of breakdown, they are not flammable and do not cause polluting leaks. The drawback of polymeric cables is their scarce ability to withstand partial discharge activity over long periods of time. Therefore, partial discharge measurements performed soon after cable laying (generally during the 1-hour AC withstand test) or on aged cables are getting a key tool to ensure reliable performance of transmission lines.

This paper introduces a novel technique for partial discharge detection, processing and diagnosis. The technique is based on the use of the information borne by the partial discharge pulse waveforms. It enables noise rejection and dealing with contribution of different sources separately and, therefore, allows accurate diagnosis to be carried out. The Measurement results enable, moreover, localization of partial discharge sources to be performed. Some practical examples of on-field partial discharge measurements and partial discharge source localization, performed applying the here presented technique, are reported and commented.

Introduction:

High voltage (HV) and medium voltage (MV) polymeric extruded power cables have achieved insulating properties comparable to those of oil-paper cables (e.g. high dielectric strength and resistivity, low dielectric losses and permittivity, low thermal resistance, chemical stability). The easy installation due to the absence of oil in the system (resulting in lower costs) made the polymeric extruded cables to replace oil-paper cables in many plants during the last years.

On the other hand, polymeric power cables (especially those made of cross linked polyethylene) are less resistant to partial discharges (PD) and to water adsorption than oil filled ones. PD, that can originate from local defects (cavities, protrusions, contaminant), mostly in cable joints and terminations, as consequence of bad installation, can lead to breakdown of the insulation. The major and most effective tool to detect local damage, defects, and/or localized aging processes in extruded cable systems is, as is well known, the measurement and analysis of PD [1]–[2]. Particularly, in the case of the HV polymeric power cables (150 kV to 400 kV), measurement of PD is performed just after the cable system installation (after laying test) in order to detect possible flaws of the insulation system that could bring to the breakdown of the system during the commissioning HV test (usually performed applying a voltage higher than the rated one for a short time interval, typically one hour), or could seriously damage the system and lead to the breakdown in the earlier stage of the service. On the other hand, PD measurements are also more and more required in MV cable networks, when failure rate is growing due e.g. to the increasing age of MV cable systems in most installations around world.

This article describes the application of an innovative PD detection and analysis tool to the diagnosis of HV and MV polymeric cable systems. The presented tool allows to separate the signals generated from the PD inside the object under test from signals coming from other objects and from the background electromagnetic noise, on the basis of the pulse waveform characteristics. After the PD pulses are separated from the other signals, the identification of the PD source is performed in an automatic way by an identification software, which is based on fuzzy logic algorithms [3]-[6] and provides information about the type of the defect of the insulating system that generates the PD. By the separation technique, the fuzzy-logic tool is applied to homogeneous classes of pulses (i.e., coming from a single source at a time), thus providing accurate identification results. Results of a PD measurement performed off-line on a cable system, rated 220 kV, just after laying, is presented and used as example of the system application. PD-generating defect identification and location are also discussed. Finally the results of online PD measurements, performed on a MV cable system, are reported together with the results of localization achieved by the Time Domain Reflectometry (TDR) technique, applied to a set of data obtained from the measurements by the separation technique. The measurement reported in this paper were performed by the TechImp PDbase and PDcheck systems.

PD Detection and Identification

The separation of PD pulses from different sources and of PD pulses from noise is based on a clustering technique that relies on a time frequency, T-W, transformation applied to each recorded pulse. Two quantities (the equivalent time length, T, and the equivalent bandwidth, W) are extracted from each detected pulse according to the following expressions [7]–[8]:

$$\tilde{s}(t) = s(t) / \sqrt{\int_0^T s(\tau)\mathrm{d}\tau}$$

$$t_0 = \int_0^T \tau \tilde{s}(\tau)\mathrm{d}\tau$$

$$T = \sqrt{\int_0^T (\tau - t_0)^2 s(\tau)^2 \mathrm{d}\tau}$$

$$W = \sqrt{\int_0^\infty f^2 s(\tau)^2 \left|\tilde{S}(f)\right|^2 \mathrm{d}f}$$

where s, $\tilde{s}$, and $\tilde{S}$ are the pulse, with time length *T*, the normalized pulse (Euclidean norm=1), and the Fourier transform of the normalized pulse, respectively. Quantities τ and *f* are integration constants in the time and frequency domain. From a geometrical point of view, t_0 is the gravity center of the pulse, whereas *T* and *W* can be regarded as the standard deviation of the pulse in the time and frequency domains.

Once projected in the so-called T-W plane, pulses coming from PD or noise, as well as pulses belonging to different PD source types, might form different clusters corresponding to pulses characterized by similar waveforms. Therefore, different clusters of pulses on the T-W plane, end up representing groups of pulses having a common source. An example of this is shown in Fig. 1, where three types of pulses (detected in a high voltage cable system) can be observed: (a) pulses with low value of equivalent frequency and high duration (e.g. IGBT commutation pulses), (b) pulses with intermediate value of equivalent frequency (possible PD pulses) and (c) pulses with high value of equivalent frequency (external electromagnetic noise). Eventually, typical representations, such as PD height-phase patterns, can be built up for the classes so that the acquired PD pattern can be divided in subpatterns showing pulse height and phase coming from a single-source type and/or location (Fig. 2). It is noteworthy that pulses belonging to noise will differ, in general, from pulses generated by PD sources.

With regard to cables, it has been observed that pulses coming from different locations belong to different clusters in the T-W map. In fact, even in cases where they are generated by the same type of defect, they face different transfer functions between the source and the sensor [9].

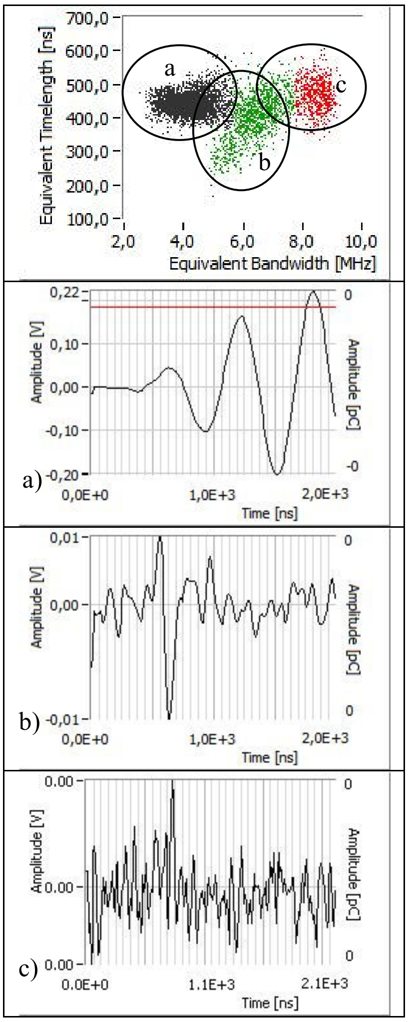

Figure 1: Example of feature extraction of different pulses. The differences, in terms of pulse shapes, result in different positioning of the pulses in the equivalent time-length/equivalent bandwidth plane.

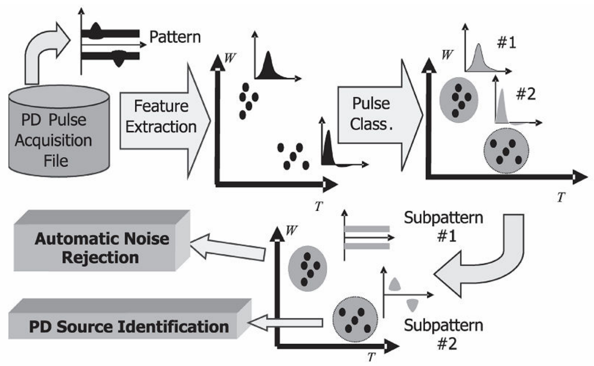

Figure 2: PD data processing. Example of two superimposed phenomena consisting of PD activity and noise. Feature extraction and separation (T-W map), pulse classification (Class.), and identification are carried out sequentially.

In particular, pulses generated by different sources located along a cable route tend to lose frequency content (lower W values, larger T values) when they have to travel from longer and longer distances to reach the measurement point [9].

The T-W map can constitute, therefore, a fundamental tool for noise rejection, PD activity separation, and even defect localization in cable systems, as discussed later.

Once different phenomena have been separated, a proper identification, to single out the type of the defect generating PD, can be achieved for each data subcluster. Automatic identification is based on fuzzy logic algorithms [3]–[5] applied to statistical markers extracted from the distribution of the pulse quantities (e.g., height, phase, and repetition rate) of each separated class. In such a way, identification becomes highly effective, because it is applied to homogeneous data sets. Noise can be recognized through statistical algorithms (for example based on correlation techniques) and then removed [3].

Identification of PD source for each subclass relies on a multi-level procedure [4]. The first level provides a broad recognition stage based on three fundamental categories, internal, surface, and corona PD, which are defined as follows. Internal PD: discharges occurring in air gaps surrounded by solid dielectric or solid dielectric and metallic electrodes involving significant components of electric field orthogonal to electrode surfaces. Surface PD: discharges that develop on surfaces of solid insulating materials, including solid-solid and solid-liquid material interfaces, which involve significant field components tangential to the surface. Corona PD: discharges produced in open air (gas) originating from a metallic object.

These categories are general enough to achieve identification with good likelihood and success rate in most cases, but they are also an initial aid for risk assessment. In fact, it is generally true that internal discharges are more harmful than surface discharges, and both are more harmful than corona discharges. According to the fuzzy nature of the inference system, a pattern may belong to all three categories, although with different degrees of likelihood, ranging from 0 to 100%. This means that a certain pattern can be traced back to a defect whose nature might be considered intermediate among the three different categories.

Two further categories, i.e. noise and invalid data, have been devised to identify and filter out possible noise, taking into account that some acquired data set may be inconsistent or not related to PD [3]. The second identification level deals mainly with defect position within the insulation, that is, the degree of closeness to HV or ground electrodes, and contains a routine that is able to detect the presence of an electrical tree, once the first level has recognized the defect as internal [4], [10]. The third level is finally able to provide specific indications on the nature of the defect generating PD for a given family of apparatuses, such as rotating machines, transformers, cables [11]. For cables, the main output categories are internal interface, external surface, and internal cavity.

Field Measurements on HV cable and localization

The results of on-site tests performed off-line on a 220 kV cross-linked polyethylene (XLPE) cable system are presented in the following. The system under test was composed of 15 cable spans, 14 sectionalized joints, and two outdoor terminations and was tested at 146 kV (phase to ground voltage) at 37 Hz using a variable frequency resonant test set (VFRTS) and acquiring PD signals from a CT (Current Transformer) installed in the link boxes (bandwidth of the sensor and detector up to 40 MHz). As a whole, the cable system proved to be PD free with the exception of a single joint (#5), where PD activity was detected below the noise level. The results relevant to this joint are shown in Fig. 3. It provides the whole PD pattern detected at Joint #5, the relevant classification (T-W) map and the subpatterns relevant to the four separated clusters (A, B, C, and D) together with examples of characteristic pulses.

Clearly, the pattern relative to the entire acquisition is the result of the overlapping of different activities. Specifically, Cluster A is associated with PD occurring along the connections between the HV bushing and the resonant test set (in fact, the equivalent frequency content is quite low). Clusters B is due to noise caused by electronic component switches in the resonant test set (correlated with test voltage). Cluster C is relevant to high frequency background noise (uncorrelated with test voltage) because of distribution circuits installed in proximity to the cable system under test. Cluster D is due to PD in joint #5. It is worthwhile mentioning that phenomena A and D are overlapped thus, without any separation tool, PD would have gone undetected, since their maximum amplitude is lower than the noise level.

The phenomena corresponding to Clusters A, B, and C were detected from all of the measurement points. In particular, the activities marked as A and B were subjected to signal attenuation and distortion, because the pulses, generated by these phenomena, were travelling from the power source to the detection point (in the case of detection from joint #5, the signals had travelled almost 3 km); Cluster C was detectable in every location, almost unchanged. On the contrary, Cluster D was detected only at the link box connected with joint #5 and was characterized by PD pulses with a large equivalent bandwidth. Therefore, the source of this PD contribution was attributed to a defect inside joint #5. The output of the fuzzy identification tool applied to the subpattern corresponding to the cluster D is reported in Fig. 4. As can be seen, the fuzzy algorithm provides a mixed response of “internal” and “surface” with a likelihood of 77 and 23% respectively, but the tree alert (not shown in Fig. 4), based on an algorithm aimed at recognizing the evolution to an electrical treeing from internal discharges, did not provide any warning. This identification is compatible with a discharge at the interface between a joint and the cable insulation. This kind of discharge can occur where there is an incorrect joint assembly.

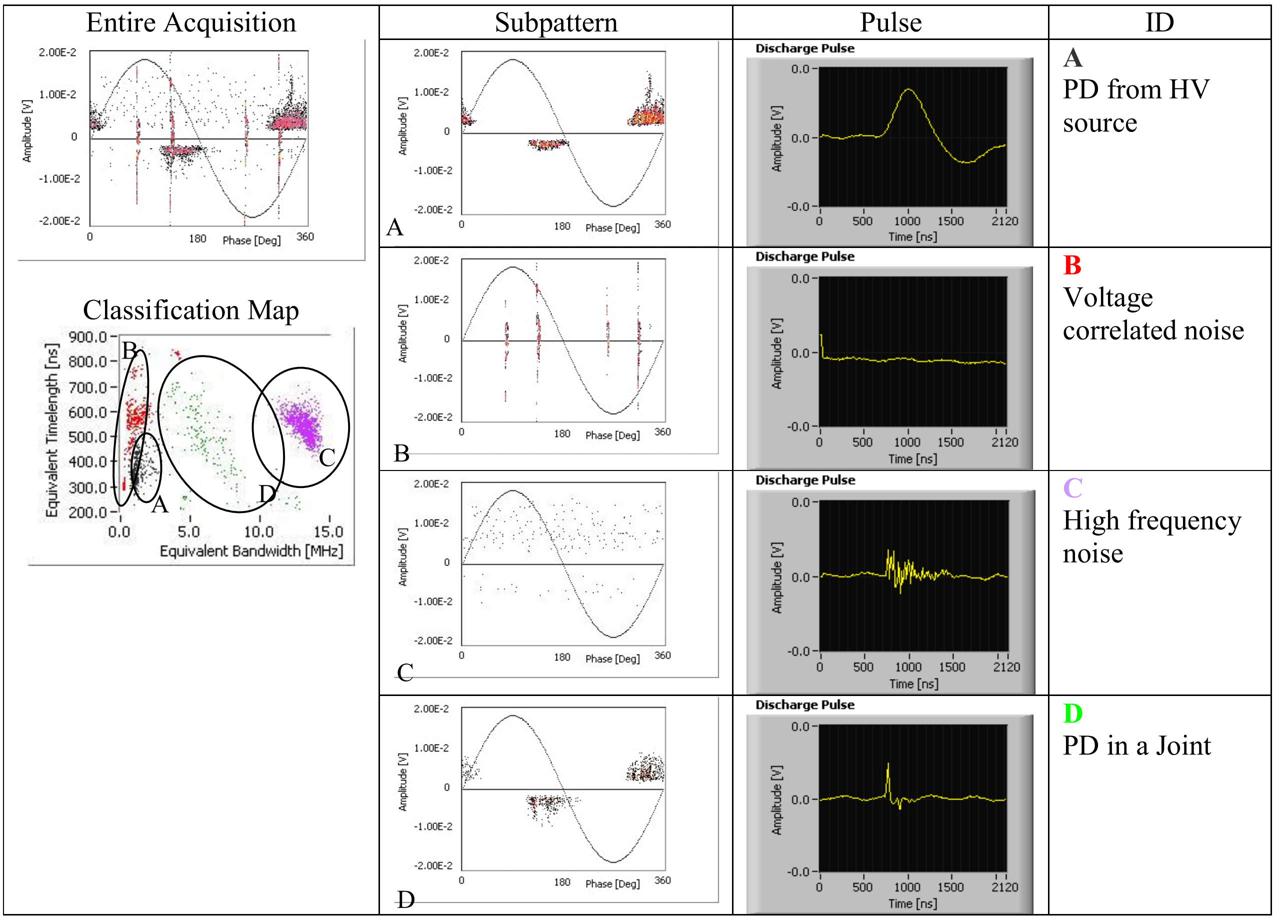

Figure 3: Sub pattern representation of classification map single classes

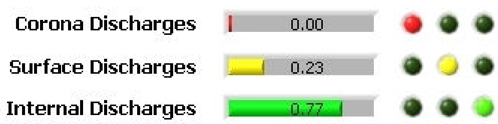

Figure 4: PD source identification relevant to the subpattern D of Fig. 3

The corrective action following the discovery of such PD was joint replacement. PD measurements were then carried out again on the newly installed joint, in this case with no indication of PD phenomena. The defective joint was analyzed in the laboratory, and forensic observations showed evidence of incorrect assembly, with the edge of the HV cable electrode just outside the shielded zone. This finding agrees with the indication of interface discharges provided by the identification system.

Localization

The acquisition of pulse waveforms allows a more effective approach to condition-based maintenance to be performed, not only through identification of the PD source, but also by localization of insulation flaws. Generally, in extended HV systems (e.g. HV cable systems), the same PD phenomenon may be detected from different measurement locations. The T-W map separation allows to obtain homogeneous (i.e. relative to the same PD phenomenon) data to be compared. Generally, the location showing, on average, larger magnitudes and W values, and lower T values is the one where the defect can be found. Moreover, propagation models can be used to fit the measurement results and to obtain more accurate indications.
In case of short cable systems, TDR can be used to assess the exact location of a PD source.

The system described in this paper is able to record the pulse waveforms with various time length (1 to 50 μs), so both the PD pulse and its reflections, generated in correspondence of the propagation impedance discontinuities, can be recorded in the same oscillograph. The analysis of the time lag between the PD pulse and its reflections provides the distance between the PD source and the measurement point.

Eventually, in long cable lines, the arrival time technique can be used to localize PD sources. It consists of the simultaneous detection of PD pulses from different measurement locations; the analysis of the time lag among the recorded pulses allows to estimate the defect position. The T-W mapping technique can be used, also in this case, to separate noise from PD and PD pulses due to different sources, allowing for a more comprehensive analysis of cable system state.

Example PD detection in a MV cable system and TDR localization

Here, an example of PD detection, separation on the T-W plane identification and localization is reported, applied to the case of on-field PD measurements performed on a medium voltage power cable system. The measurements were performed online. A part of each cable has polymeric insulation (EPR), the other part is paper-oil insulated, with a transition joint between the two parts. Partial discharge measurements, performed by the described method, showed that an internal partial discharge activity was present in the insulation system. The measurement results are reported in Fig. 5, together with the PD pattern of the detected phenomenon, obtained from the entire acquisition by classification on the T-W map, and with the output of the automatic identification system.

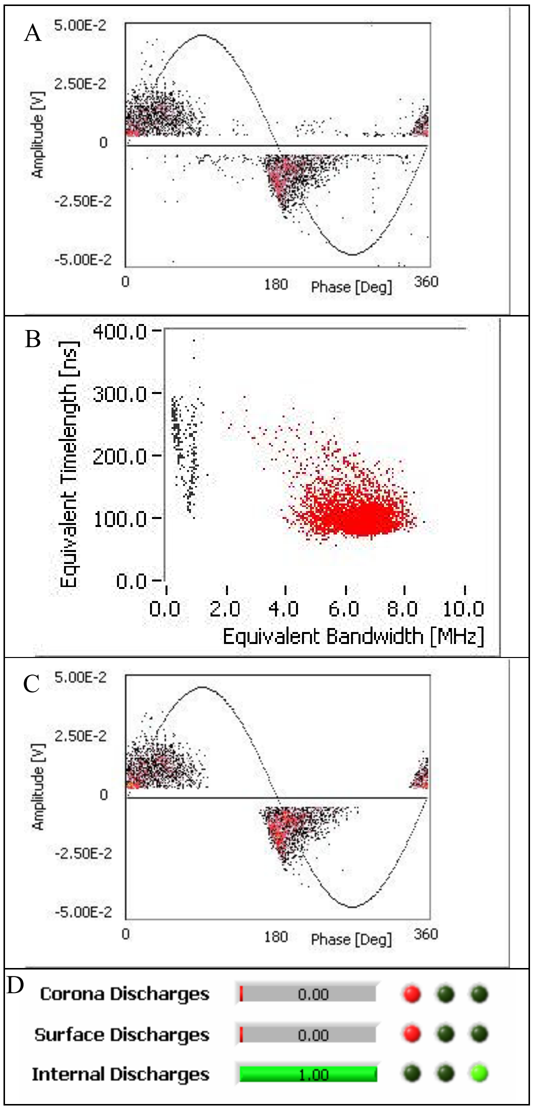

Figure 5: Measurement results performed on an online medium voltage cable. A) Entire pattern acquisition; B) Classification map; C) Sub-pattern corresponding to the red cluster on the classification map; D) Output of the automatic identification.

An example of pulse, extracted from those belonging to the red cluster of Fig. 5.B, is reported in Fig. 6.A. An averaging process, performed on a homogeneous cluster of pulses, allows to reduce the noise level and to make clearly visible the original PD pulse and its reflections at the cable terminations, as shown in Fig. 6 (wavelet transformation can be also applied, when pulses are distorted significantly).

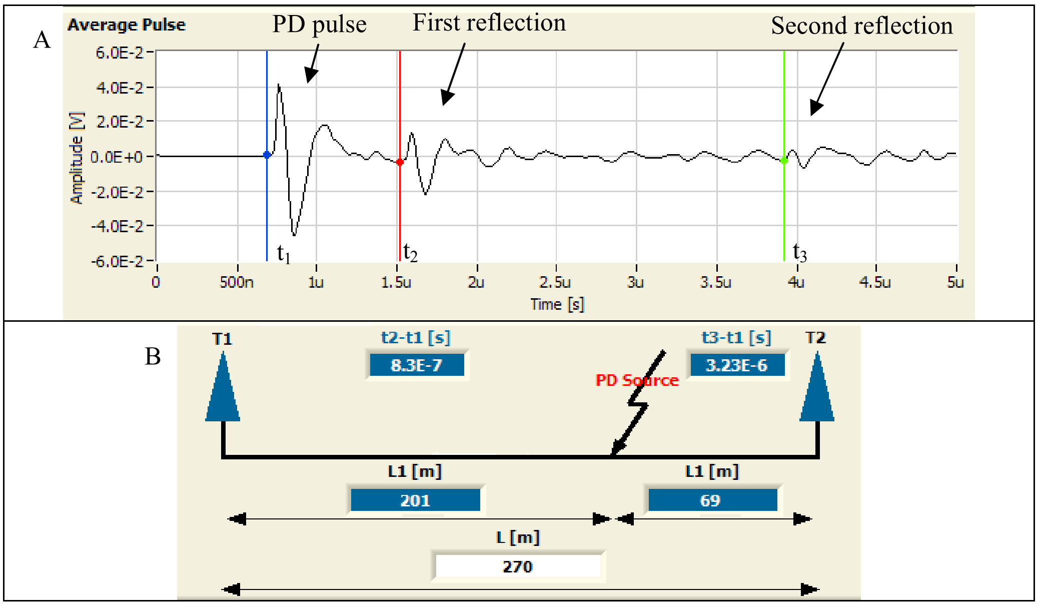

Figure 6: Results of the PD localization by the TDR technique, performed on a homogeneous cluster of waveform. A) Average pulse waveform; B) Localization of the PD source.

The analysis of the time lag among the PD pulse and the reflections, as shown in Fig. 6.B, indicate that the PD source is located at about 200 m from the terminal 1 (detection point), corresponding to the exact location of transition joint. It is noteworthy that almost one month after these measurements, the cable failed exactly in the joint indicated as affected by PD, after having shown a growing amplitude trend.

Conclusions

The PD assessment procedure here discussed can be very effective for on-site cable diagnosis. Actually, the method of separation based on the decomposition of the pulse frequency and time characteristics allows enhanced noise rejection and PD separation to be achieved; artificial intelligence methods applied to homogeneous PD data sets prove to be very effective for PD source identification. Thus, the combination of "separation and identification" leads to improved reliability of PD evaluation and diagnosis. Therefore the presented technique, provides information that can be exploited to enhance maintenance procedure plans. This is fundamental in reducing operational costs in a utility cable network. Moreover, not only did the time-frequency analysis prove to be effective for the separation of different sources of PD, but also for PD location. The latter can be strengthen by the Time Domain approach, which, however, can be strengthened significantly using the time-frequency separation of PD pulses. In such a way, in fact, only pulses coming for a certain source, which is evaluated as internal to the cable system, can be processed.

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