11073 2022 Paris Session
Study Committee SC B1 (Insulated Cables),
PS1 (Preferential Subject)

# Advanced Analysis of Partial Discharges and Breakdowns on HVDC Power Cables

**Erik WINKELMANN[*1,2], Iaroslav SHEVCHENKO[1,3], Christoph STEINER[1], Peter STEINER[2], Christian KLEINER[2], Uwe KALTENBORN[1], Peter BIRKHOLZ[2], Frank BÖHME[1], Andreas KÜCHLER[4], Markus H. ZINK[4], Stefan KORNHUBER[5], Harald SCHWARZ[3], Thomas STEINER[1], Sacha MARKALOUS[1]**

**[1]HIGHVOLT Prüftechnik Dresden GmbH, Germany**
**[2]Technische Universität Dresden, Germany**
**[3]Brandenburg University of Technology Cottbus-Senftenberg, Germany**
**[4]University of Applied Sciences Würzburg-Schweinfurt, Germany**
**[5]University of Applied Sciences Zittau/Görlitz, Germany**
**[*]e.winkelmann@highvolt.com**

**SUMMARY**

The electric power system is undergoing a tremendous transition. Despite increasing energy demands resulting from an "all-electric society", on-shore as well as off-shore renewable generation units require solutions for bulk energy transportation. Here long and very long HVDC cable systems are a key enabling technology, especially land cables, to increase the social acceptance for large infrastructure projects. Reliability and availability of these systems are of tremendous importance to guarantee the payoff of the investment as well as to minimize contingency costs due to failures. A solution could be a monitoring system able to supervise cables and to identify evolving failures with high accuracy. Here the partial discharge (PD) measurement is a suitable tool. Unfortunately, conventional PD measurement concepts are not applicable at DC voltages. The PD monitoring system presented in this article uses a new approach to identify and characterize PDs under DC. Here, the signals are coupled by a newly designed High Frequency Current Transformer (HFCT). A real-time algorithm is differentiating noise from deterministic signals, whereas these signals are analysed by machine learning methods to cluster them. Utilizing an algorithm like Linear Predictive Coding (LPC) allows a significant reduction of the amount of data and enables the reconstruction of the original signal form for further analysis and characterization.
Peculiarities of HVDC cable systems show effects like space charge accumulation, interface charge injection and others with the potential to lead to breakdowns without preceded PD activities. Therefore, any monitoring system must include a fault location functionality. Typical fault locators use voltage dividers as coupling devices. Our work showed that it is possible to utilize the described HFCT instead of conventional dividers to reach identical accuracy for the fault localization. This enables an easy integration of a complete dielectric cable monitoring system for existing and new cable systems which is galvanically decoupled.

**KEYWORDS**

Cable Monitoring, Power Cable, Fault Localization, Partial Discharge, Direct Current

## 1. Introduction

Power cables are playing an increasingly important role in the future development of power grids worldwide. This development is driven by several factors. On the one hand, both energy demand and the structure of energy sources are changing. On the other hand, modern mobility concepts, for example, are based on electricity. This can be described as the change to an "all-electric world" in which most areas of life and industrial structures are powered by electric energy. Electricity is increasingly generated in a decentralized and distributed manner from renewable energy sources. Particularly important in this context are offshore wind farms, whose generating units are interconnected with power cables and ultimately connected to the respective grid via a cable link. The volatile nature of renewable energy sources such as wind and sun increases the need for national and international grid reinforcement to better compensate for fluctuations in the energy grid. In addition, cables are increasingly being used instead of overhead lines due to limited public acceptance of new overhead line systems. The focus of this paper is put on HVDC cable systems, which enable an efficient transmission of large amounts of energy over very long distances based on power electronic converters, preferably voltage source converters.

In Germany, several HVDC land cable routes of up to 700 km in length are being planned with the so-called corridor projects to transport renewable energy from the north to the industrial centers in the south of the country [1]. The German TSOs have jointly decided to use a voltage of 525 kV DC for these projects, so that one cable system has a capacity of 2 GW [2]. In the United States, a similar project, SOO Green, with a length of about 560 km and a transmission capacity of up to 2.1 GW, is in planning state to transmit energy generated from renewable sources [3]. The power of 3.8 GW from renewable energy sources is to be transmitted in the Xlinks project from Morocco to the UK. In total, the connection has a length of approx. 3800 km [4]. In addition to these projects, there are many other HVDC cable projects in preparation or already in planning worldwide.

If unplanned outages occur in projects with such high transmission capacities, extensive and costly re-dispatching measures must be initiated [5]. Therefore, it is of critical importance to be able to quickly localize any faults that occur along the several 100 km of cable or, in the best case, to be able to identify evolving faults in advance and maintain them in the event of planned outages. This paper addresses the associated challenges and presents a solution to both: the monitoring of the whole cable system as well as the pinpointing of a sudden breakdown of the insulating system.

## 2. Lifetime Quality Assurance of an HVDC Power Cable

The economic, technical and organisational expenses for planning, installation and operation of extra-long HVDC cable systems are only justified if a very long operating time can be guaranteed. Typically, such systems are planned to be in operation for at least 40 years before extensive replacement becomes necessary. To achieve this, sensitive and complete quality assurance is required. A summary of all quality related tests can be found in the recently published CIGRE brochure 852 [6]. Before a power cable can be commercially distributed, numerous tests must be successfully passed. Passing the Prequalification Test, the Extension of Qualification Test and the Type Test proves the technical suitability of the cable for the respective application. If these tests are passed successfully, they do not have to be repeated. The quality of subsequently manufactured cables of the same type is then proven in so-called routine tests or, to a small extent, in sample tests. The results of the tests and measurements are documented and must be within previously defined tolerances or limits derived from the type tests. After successful testing, the cable can leave the factory and be transported to the place of use. There, the cable is laid and connected to other cable segments or to switchgears by means of joints or terminations. The cable is subjected to high stress levels during this process caused by transport, handling, and mechanical impact like bending. Due to the complexity of the assembly process, joints and terminations installed on site are potential weak points in the cable system. Therefore, so-called after-laying or commissioning tests are recommended to prove that all components meet the quality requirements. Figure 1 qualitatively shows the typical stresses (electrical, mechanical and thermal) on a power cable over its lifetime after manufacturing. After-laying tests are usually the last quality assurance measures before the cable is put into operation. Therefore, it is of utmost importance to perform a sensitive partial discharge (PD) measurement during this test, especially at all joints and terminations, as prescribed in [7].

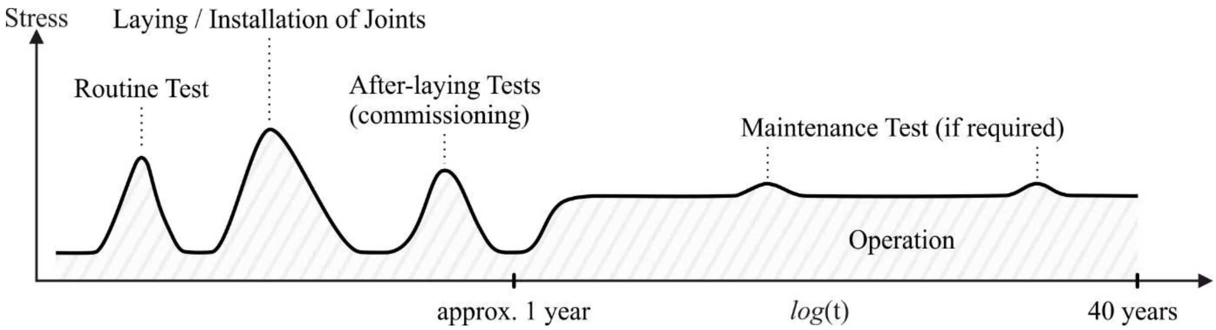


Figure 1: Qualitative Stress-Time-plot of a power cable

For DC cable systems, in addition to the native DC voltage withstand test, an AC test at frequencies between 10 and 300 Hz with an accompanying PD measurement is recommended, to enable a reliable and sensitive measurement of the cable with all installed joints and terminations. Frequency range and test duration are chosen to guarantee the inception of PDs of potential defects. When all after-laying tests have been performed successfully, the cable system can be put into operation and the longest chapter of the cable system's life cycle begins: the operation. In this phase, monitoring systems can provide valuable information on the condition of the cable system or pinpoint evolving faults that might lead to failure. The analysis of PD signals as an early warning of a potential breakdown enables the avoidance of an unplanned outage. Due to different breakdown mechanisms the required reaction time ranges from few seconds to weeks and months.
In case of a sudden breakdown, the fault must be localized as quickly as possible in order to be able to carry out a repair and ultimately put the cable back into operation.

## 3. Cable System Monitoring

### 3.1. General Concept: PD Monitoring and Fault Locator

In order to detect faults at early stages and to enable rapid fault localization after a potential breakdown of the cable system, two systems are required. Those differ considerably due to the properties of the resulting signals:

- PDs lead to comparatively small signals that propagate along the conductor and are damped and deformed according to the transmission properties of the cable.
- A breakdown in the cable system leads to a massive travelling wave along the conductor and is still clearly detectable even over long distances.

This difference led to two solutions, each focused specifically on one of the explained tasks: A PD measurement system and Fault Locator for breakdown localization purposes. To better explain the resulting topology of the monitoring system, Figure 2 shows an example of an HVDC cable system consisting of two converter stations coupling the near and far end of the system to the AC transmission grid. From left to right: a long underground cable is connected to a long submarine cable with a cable transition station. The far end of the submarine cable is connected to the second converter with an overhead line.
Long HVDC cable systems require a large number of joints, which are potential weak points. Equipping each of these joints with a PD measurement technology, as commonly done for AC cable monitoring systems, is not suitable for long HVDC land cable systems due to economic and technical reasons. The sensitivity of the developed PD measuring system allows the surveillance of every joint in between two measuring points with a distance of up to 12 km. This makes the system ideal for installation in grounding boxes, which in typical HVDC cable are several km apart from each other (Figure 2).

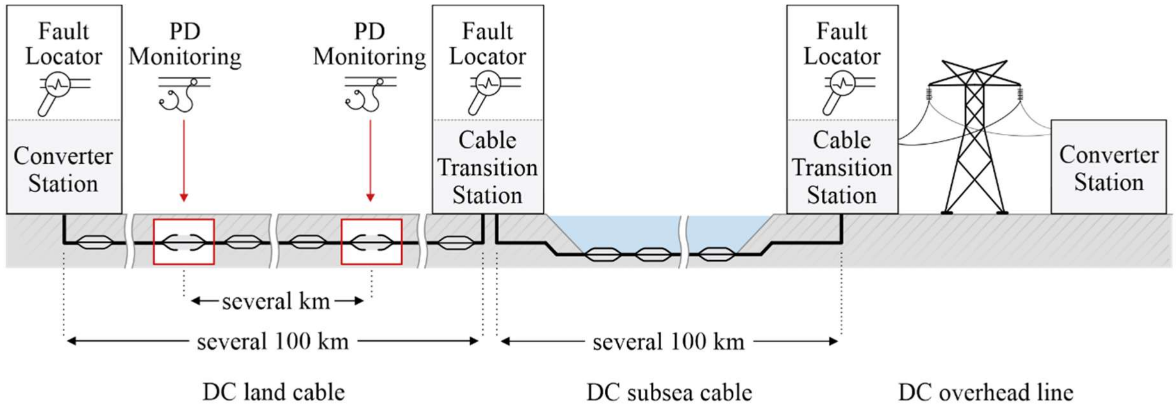

Figure 2: Example of an HVDC transmission system with a PD monitoring system and a Fault Locator installed

Contrarily to the early-stage PD faults, in the case of a breakdown a travelling wave with a very high amplitude propagates through the cable system. Pronounced changes in the wave impedance, e.g., at cable transition stations or at the transition from a cable to an overhead line, lead to the partial reflection of the incoming wave and the transmitted wave might be strongly attenuated. Therefore, a Fault Locator system should be installed at every cable transition station and at the near and far end of the cable system in order to capture the required signals for an immediate pinpointing of the fault. The fault location can be determined using time domain reflectometry (TDR), which is enhanced with signal processing methods to allow automatic detection of the fault location with high accuracy.

### 3.2. Comparison of Signal Coupling Techniques

Capacitive and inductive approaches of coupling have led to two common devices: capacitive or ohmic-capacitive voltage dividers and High Frequency Current Transformers (HFCTs). An HV divider is the most common device for PD coupling as it is compliant with IEC 60270 [8]. Even though the coupling is performed via the electric field, a divider exploits a galvanic connection to the HV potential of the device under test (DUT), which therefore defines the geometry and overall design by the necessity to provide enough clearance and other design features of HV equipment. Being an indispensable device for testing energy distribution and transmission equipment in the factory, it has a limited use for testing and monitoring of cable lines. While a capacitive divider in the classic test field acts as the signal path of a high-frequency signal such as a PD, in the case of the cable line this task is taken over by the cable itself. The divider in this case represents the coupling quadrupole, however, this function can be fulfilled by an HFCT. As a magnetic field-coupled device, an HFCT does not require pre-installation and can easily be integrated into new and existing cable systems. These particularities made it the most common non-conventional type of the PD coupling device.

Another consideration is the general comparison between the nature of coupling (electric or magnetic field) and the actual frequency band of signals to be acquired. Signal extraction by the means of the capacitive coupling gets more effective with frequency. Contrarily, the cable acts as a low-pass filter and therefore lowest frequency components propagate the highest distances and are of most interest for the monitoring purposes. Hence, in cable quality assessment capacitive coupling might focus on the wrong part of the frequency spectrum. Furthermore, an HFCT has a few tuning parameters, e.g. permeability of the magnetic core, that can be changed to fit its band-pass-behavior to the desired part of the spectrum.

### 3.3. Fault Locator

The Fault Locator is an established product that is broadly used for different applications. Apart from monitoring purposes, it is also used for factory or on-site tests in combination with an HV test system [9, 10]. The Fault Locator solution comprises several components: the coupling device, the transient recording hardware and the software for fault localization. The latter can be incorporated in the testing control system or designed as a stand-alone device. As coupling device the Fault Locator conventionally uses a common capacitive or ohmic-capacitive divider. In addition to that, this paper presents the coupling utilizing an HFCT. The carried out measurements underline the advantage of the HFCT coupling in comparison to the conventional divider solution.

### 3.4. PD Monitoring: State of Development

One of the biggest challenges with HVDC PD measurements is the interpretation of the results. In AC PD measurements, so-called phase-resolved histograms are analyzed and interpreted to classify any PD that might occur. These known patterns do not exist with DC voltage due to the lack of periodicity. A robust interpretation of partial discharge measurements under DC voltage is the subject of ongoing research [11, 12].
To advance on this topic the authors have started with proposing an approach named “TruePD” [13]. Its aim is to separate PD signals from the noise and to feed them in full length into further processing. A real-time capable realization of this approach was presented in [14] as “Event Trigger”. Deterministic signals (Events) are separated from the noise and described with representative linear predictive coding (LPC) coefficients [15]. These coefficients later build the basis for clustering, allow a reconstruction of the coded signal while enabling a drastic data reduction. Further implementation of the developed Event Trigger was published along with the topic of PD source localization in [16, 17]. Details concerning the HFCT design and further issues concerning coupling to the cable were discussed in [18].
Promising approaches to interpret DC PD measurements are based on pulse sequence analysis, as for example reported in [11]. The approach works very well as long as only one partial discharge source is present. However, if there are several signal sources present, the approach of analyzing the properties of two consecutive pulses may not work. Only a clear assignment of all occurring signals to their defined sources could remedy this. This paper presents a measurement and the evaluation using the core algorithms of the PD monitoring system. With the use of intelligent signal processing and machine learning, signals are assigned to the corresponding sources and advanced statistical evaluation is made possible.

## 4. Measurements

### 4.1. Fault Locator: Divider- and HFCT-coupling

In order to compare the evaluation of a breakdown event in the cable system by means of a classical divider and an HFCT, a test setup according to Figure 3 was used. The HFCT as well as the divider were connected to the Fault Locator. A spark gap was installed between the inner conductor and the shield of the cable near Joint 2 (J2). At approx. 10 kV DC, a breakdown occurred at the spark gap and the trigger of the Fault Locator and thus the recording of the signals over several hundred µs with a sampling rate of 250 MS/s was triggered. A direct comparison of the two signals is not possible, because the divider measures the step response resulting from the breakdown and the sudden change of the voltage from approx. 10 kV DC to ground potential, while the HFCT generates an output voltage that is proportional to the first derivate of the conductor current.

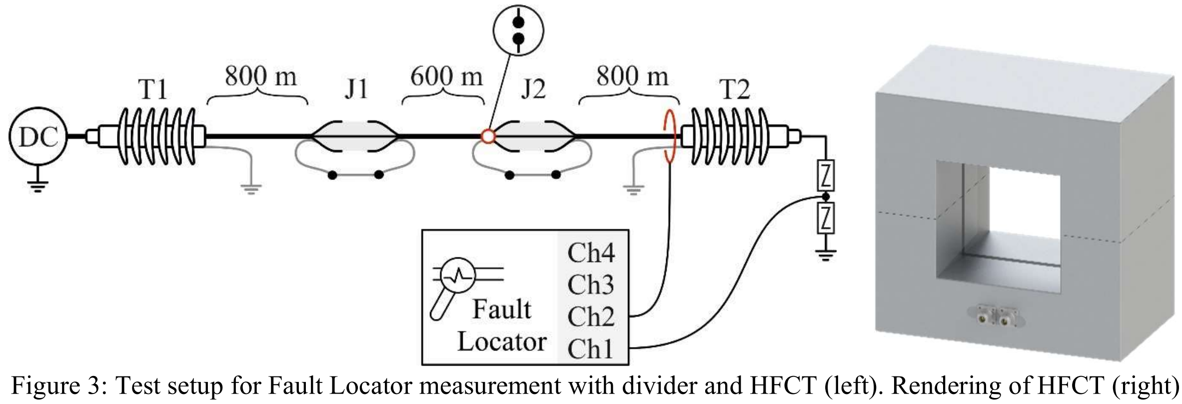


Figure 3: Test setup for Fault Locator measurement with divider and HFCT (left). Rendering of HFCT (right).

The pre-processing of the measured signals consists of a filtering with a linear-phase low-pass filter with 256 taps and a cutoff-frequency at 5 MHz, which is applied directly to the signals from the divider and the HFCT. This is done to suppress high-frequency content or electromagnetic interference coupling. In the next step, the impulse response is obtained by calculating the first derivate of the measured step response of the divider (Figure 4 a)). This allows the direct comparison of the two signals measured from the divider and the HFCT as shown in the Figure 4 a) and b). Both corresponding signals are further preprocessed, i.e. normalized, rectified and scaled by squaring each sample as shown in Figure 4 c) and d). After these steps, the first peak can be easily found because its amplitude is always one.

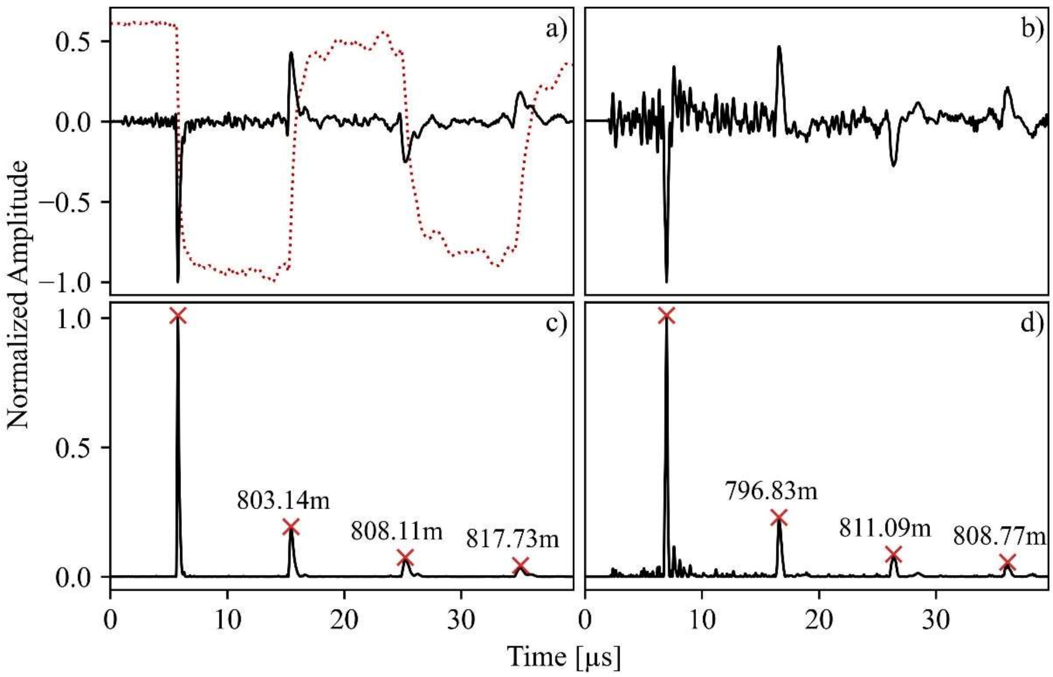


Figure 4: Comparison of the breakdown measurement for divider and HFCT, where a) shows the signal measured with the divider (dashed) and its first derivative (solid) and b) displays the signals measured with the HFCT. c) and d) show the squared curves of a) and b) respectively as well as the calculated fault locations by means of TDR. All curves are normalized to their maximum value.

The time between two successive peaks of each curve corresponds to twice the distance of the fault, as the wave originating from the fault travels to the measuring point - gets reflected - propagates back to the fault - is reflected again - and travels back to the measuring point until the signal is fully attenuated. Due to the exponential decay of the signal energy, the boundary condition that a decreasing energy is expected between the first peak (amplitude of one) and subsequent peaks can be formulated. This means that all local peaks between the first peak with an amplitude of one and the following peak are ignored when a subsequent peak with higher amplitude is detected. Now using TDR, by considering the propagation velocity which was determined according to [10] with 165.8 m/µs, and the time difference between two successive peaks, the distance between the measuring point and the fault is calculated. Both coupling methods show similar results that differ less than 1%. Usually, the first reflection is evaluated which for both coupling methods yields a remarkable accuracy with a failure related to total cable length of less than 0.2% as shown in Table 1.

Table 1: Localization results for divider and HFCT for several reflections

| Coupling method | Divider | | | HFCT | | |
|---|---|---|---|---|---|---|
| Total cable length | 2200 m | | | | | |
| Reflection # | 1 | 2 | 3 | 1 | 2 | 3 |
| Fault distance | 803 m | 808 m | 818 m | 797 m | 811 m | 809 m |
| Failure related to total cable length | ≈ 0.14% | ≈ 0.37% | ≈ 0.82% | ≈ 0.14% | ≈ 0.5% | ≈ 0.41% |

4.2. PD Monitoring: Differentiation of sources as basis for clustering

A test setup consisting of a DC source, a 2.2 km long medium voltage cable, and a corona discharge was used to identify PDs (Figure 5).

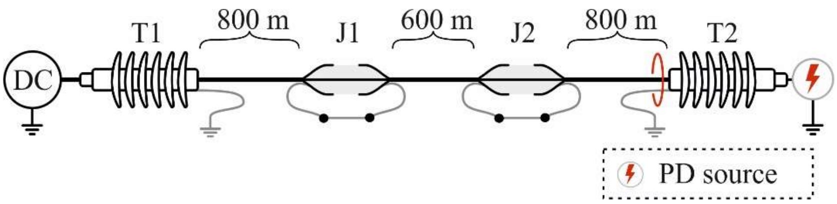


Figure 5: Test setup for corona discharges at a cable under DC voltage

The voltage was increased up to the PD inception voltage and the PD monitoring system was used to acquire and evaluate the signals coupled out with an HFCT. In addition to the corona discharges, an unknown number of disturbances were present. Consequently, different signal sources were suspected. The PD monitoring system should detect all occurring signals, cut them out of the data stream and among others extract the 6th-order LPC coefficients, which describe each signal with only seven coefficients, regardless of the signal length. This is a requirement for further analyzing the signals using the toolchain of machine learning techniques in Figure 6. The individual steps of this toolchain are explained as follows:

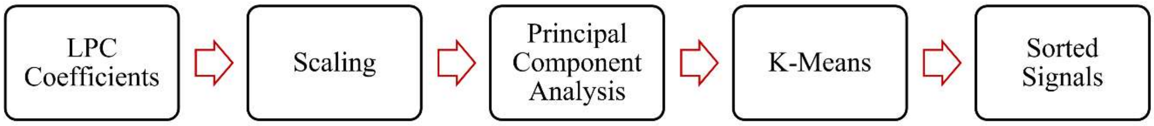


Figure 6: Machine learning toolchain to automatically sort the recorded signals according to their similarity. All LPC coefficients are rescaled column-wise to zero mean and unitary variance. With principal component analysis (PCA), the principal components are extracted to reduce the dimensionality. The reduced feature set is clustered using the K-Means algorithm in order to sort the signals according to their similarity.

All LPC coefficients have different value ranges and are rescaled to zero mean and normalized to unitary variance. Next, PCA [19], which is a statistical method to determine the most important components of a high-dimensional dataset and reduce the dimensionality by rotating the coordinate system in the directions of the main components, can help to remove features that do not carry important information. This can be demonstrated with the Pareto chart in Figure 7. Here, the explained variance of the dataset by each of the seven main components is visualized as a bar. The red line indicates the accumulated variance that must reach 100% for seven main components. Two important conclusions can be extracted from this Pareto chart:

1. With only three components, more than 95% of the entire variance in the dataset is explained. This indicates that we can disregard the remaining four principal components for the further steps in the tool chain.
2. The last three main components explain almost no variance. In particular, the last main component explains 0% variance. This represents the first LPC coefficient, which is always one.

As a result, from the Pareto chart analysis, we only use the first three main components to sort the signals using the K-Means algorithm [20].

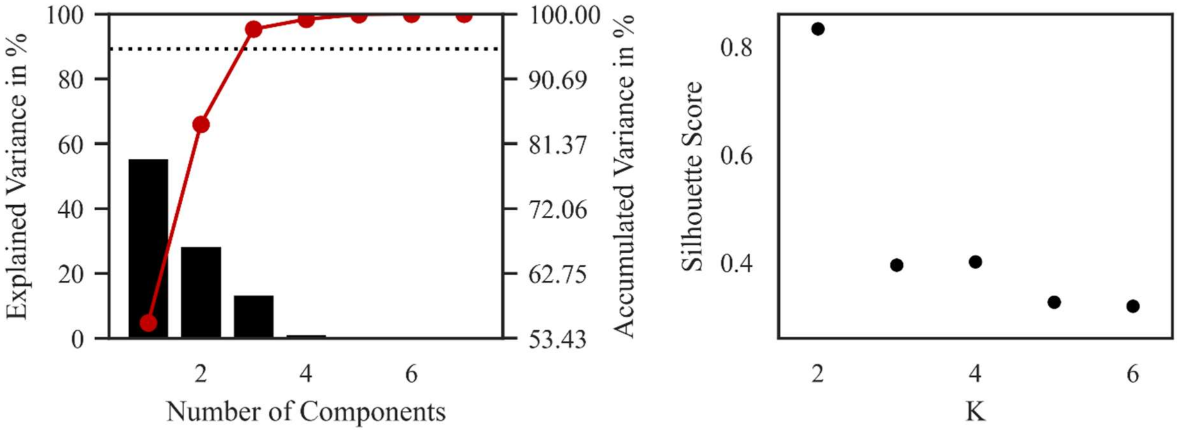


Figure 7: On the left is the explained variance by each main component (bars) and the accumulated explained variance (red line). More than 95% of the variance is explained by three components as indicated by the dashed horizontal line. The right plot shows the silhouette score for different number of clusters (K). K=2 led to the highest score and thus the ideal number of clusters is two.

The K-Means algorithm is an unsupervised learning method that assigns observations to K cluster centers (centroids). Various scores exist to optimize the K-Means algorithm. In this paper, we optimized the Silhouette Score [21], which essentially computes the mean intra-cluster distance and the mean nearest-cluster distance for each signal. It is 1 if the clusters are well separable and -1 if it is likely that the signals were assigned to the wrong clusters, which is the case for overlapping clusters. In Figure 7 (right), the Silhouette scores for different numbers of clusters (K) are visualized. The highest score is reached with K=2 which indicates that two kinds of signals can be well separated.

In Figure 8, the results of applying the K-Means algorithm with two centroids on the signals are visualized. It can be observed that the determined ideal number of two clusters is indeed suitable for clustering the dataset. Obviously, there are two groups of signals in the dataset, which the K-Means algorithm was successfully able to cluster. One of these clusters is likely to indicate a corona discharge, whereas the other is expected to represent a disturbance.

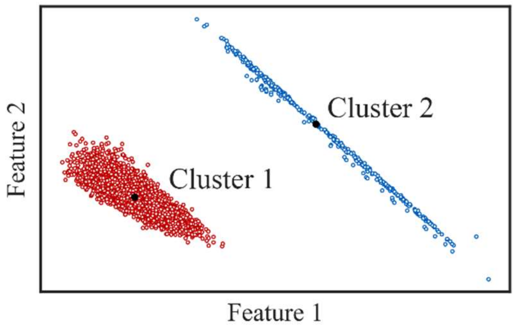


Figure 8: The first two main components of the signals and the cluster centroids obtained by the K-Means algorithm. The colors encode the cluster labels the signals were assigned to.

Figure 9 shows a histogram of the time differences between assignments to the same clusters. The histogram of Cluster 1 shows a broad distribution, resembling a normal distribution. Since corona discharges occur stochastically, it is very likely that this cluster indicates corona discharges. The second cluster occurs strictly periodically. This indicates that a periodic distortion is present (period of 10 ms) in the dataset and confirms the hypothesis that Cluster 1 should be the corona discharge.

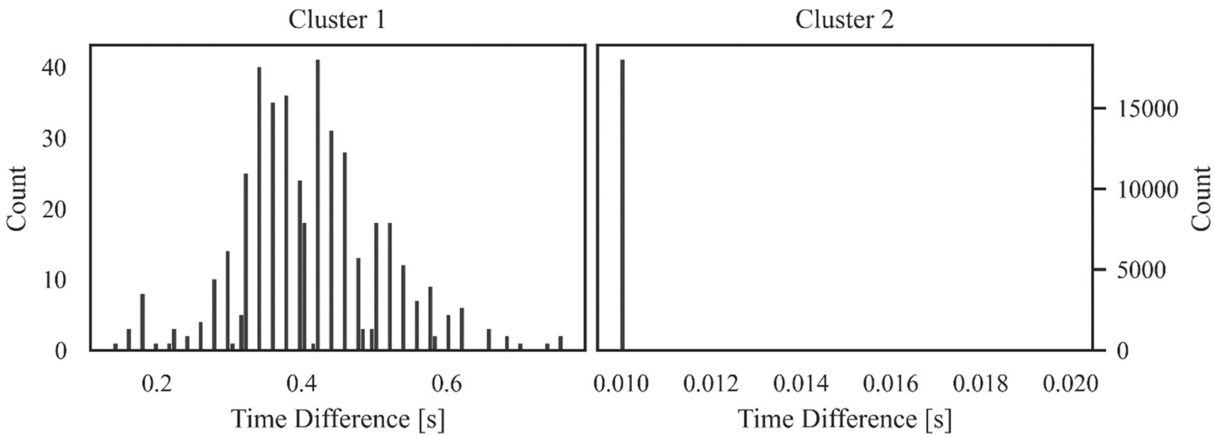

Figure 9: Histograms visualizing the Time Difference between two occurring signals of the same source vs. Count (180 s measurement)

The "TruePD" system not only extracts the LPC coefficients of each detected signal. The length and signal energy of each signal are also determined. Figure 10 presents a Kernel Density Estimate (KDE) plot for both clusters, showing the signal length versus signal energy and their density distribution. The energy of the signals is proportional to the charge according to IEC 60270, so that a later standard-compliant evaluation is possible.

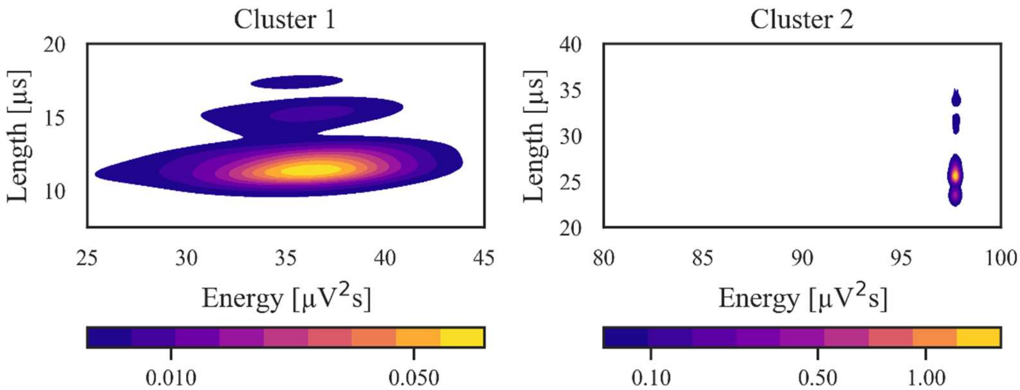


Figure 10: Kernel Density Estimate (KDE) plot to describe the distribution of the signal energy with respect to the length of the detected signals.

While cluster 1 has a broad energy distribution from approx. 26 $\mu V^2s$ to approx. 43 $\mu V^2s$, cluster 2 has an almost stable energy of approx. 97 $\mu V^2s$. This clearly shows that the signals belonging to the cluster 2 represent a stable noise source with a constant energy content. Cluster 1, on the other hand, shows an expected broader distribution, which suggests a real PD source.

## 5. Conclusion and Outlook

Both, the PD monitoring system and the Fault Locator, can be operated with an HFCT enabling a convenient integration into new and existing AC and DC cable systems. The integration of a divider for online fault location is no longer necessary, which reduces implementation effort and costs and increases reliability. By using robust signal processing, the localization error of a breakdown when evaluating the first reflection is less than 0.2 %. The evaluation of subsequent reflections leads to errors less than 1 % due to the pronounced dispersion of the cable. Here, the use of further advanced signal processing can increase the localization accuracy.

The PD monitoring system based on “TruePD” covers a distance of up to 12 km between two measuring points. This allows an efficient integration into very long land cable systems. In addition to the discussed HVDC applications, the system is also suitable for typical AC cable systems, where it would only have

to be installed at the near and far end. Proof of the sensitivity of the system was provided in [17]. There, a 20 pC PD pulse was detected after 6.6 km, which corresponds to a maximum possible distance between two measuring points of approx. 13 km. The carried out feature extraction was described extensively in [14] and enables a reconstruction of the signal afterwards and thus also a PD evaluation according to IEC 60270, for example.
Machine learning algorithms in combination with real-time signal processing allow advanced statistical evaluation of PD signals and disturbances. This information can be used to classify different PD sources and generalize the behavior of those. On this basis, predictive maintenance, i.e. the use of planned outages to replace faulty components will be developed. Nevertheless, faults can evolve very quickly, so that PD activity is immediately followed by a breakdown. For such faults, online localization makes the difference, as valuable time can be saved in contrast to time-consuming fault localization afterwards. As a result, especially in cable systems with high transmission capacities, reliability and availability can be increased while reducing redispatch, repair and outage costs.

## BIBLIOGRAPHY


[1] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH. Grid Development Plan 2035 (2021). 2nd ed., 2021. [Online]. Available: http://www.netzentwicklungsplan.de

[2] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH. Übertragungsnetzbetreiber setzen auf technische Innovation bei Gleichstromerdkabeln. 2021.[Online]. Available: https://www.tennet.eu/de/news/news/uebertragungsnetzbetreiber-setzen-auf-technische-innovation-bei-gleichstromerdkabeln

[3] Direct Connect Development Company. SOO Green HVDC Link: Project Overview. Accessed: Dec. 12, 2021. [Online Video]. Available: https://www.soogreenrr.com/project-overview/

[4] Xlinks: Morocco UK Power Project. [Online]. Available: https://xlinks.co/morocco-uk-power-project/

[5] ENTSOE Transparency Project. Costs of Congestion Management. [Online]. Available: https://transparency.entsoe.eu/congestion-management/r2/costs/show

[6] CIGRE WG B1.62, "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV," CIGRE Tech. Rep. 852, 2021.

[7] CIGRE WG B1.38, "After laying tests on ac and dc cable systems with new technologies," CIGRE Tech. Rep. 841, 2021.

[8] High-voltage test techniques - Partial discharge measurements, Std. IEC60 270:2000+AMD1:2015, Nov. 2015

[9] 5.50-1/2 HiRES Locator, HIGHVOLT Prüftechnik Dresden GmbH (2018/10). [Press release]. Available: https://www.highvolt.de/portaldata/1/Resources/HV/Downloads/5-50-1-de.pdf

[10] F. Böhme, R. Pietsch, U. Kaltenborn and M. Hensel "Cable Fault Location in High Voltage Cables – A New Solution," 2019 IEEE PES GTD Asia, pp. 406- 410, March 2019.

[11] A. Pirker and U. Schichler, "Partial discharge measurement at dc voltage — evaluation and characterization by NoDi∗ pattern," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 25, no. 3, pp. 883–891, 2018.

[12] B. Hochbrückner, M. Spiertz, M. H. Zink, A. Küchler, and K. Backhaus, ¨ "Comparison of algorithms for clustering of partial discharge signals under dc voltage," in 2019 2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS), 2019, pp. 041–046

[13] Erik Winkelmann, Christoph Steiner, Iaroslav Shevchenko, et al., „Influence of the permitted parameter variations on the determined QIEC value according to IEC 60270," in VDE High Voltage Technology 2020; ETG-Symposium, pages 418–423, 2020.

[14] E. Winkelmann, C. Steiner, I. Shevchenko, P. Steiner, P. Birkholz, and U. Kaltenborn, "Machine learning based evaluation of dynamic events in medium voltage grid components," in Proc. 27th Int. Conf. Electricity Distrib., no. 108, 2021.

[15] J. Makhoul. Linear prediction: A tutorial review. Proceedings of the IEEE, 63(4):561–580, April 1975.

[16] E. Winkelmann, I. Shevchenko, C. Steiner et al., “Monitoring of Partial Discharges in HVDC Power Cables,” in IEEE Electrical Insulation Magazine, vol. 38, no. 1, pp. 7-18, January/February 2022.

[17] E. Winkelmann, C. Kleiner, I. Shevchenko et al., “A novel approach for a highly sensitive localization of dielectric defects in cable systems based on an adaptive model,” in Proc. 2021 Int. ETG Congr., pp. 554–560, May 2021.

[18] I. Shevchenko, E. Winkelmann, C. Steiner, U. Kaltenborn, H. Schwarz, and T. Steiner, “Grid compatibility of a high frequency current transformer designed for coupling to the cable central conductor,” to be published.

[19] Michael E. Tipping and Christopher M. Bishop, “Mixtures of probabilistic principal component analysers,” Neural Computation 11(2), pp. 443 – 482. MIT Press, June 2006.

[20] S. Lloyd, “Least squares quantization in PCM,” IEEE Transactions on Information Theory, vol. 28, no. 2, pp. 129 – 137, March 1982.

[21] Peter J. Rousseeuw, “Silhouettes: A graphical aid to the interpretation and validation of cluster analysis,” Journal of Computational and Applied Mathematics, vol. 20 (1987), pp. 53 – 65, November 1987.