

Application Note

PD measurement and localization on power cables with the MPD 800 under sinusoidal VLF test voltage

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Related OMICRON Product

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Abstract

Energizing power equipment, such as power cables, can be challenging due to the enormous capacitive load. Reducing the test frequencies down to 0.1 Hz or even lower is one approach to overcome this challenge. Performing a partial discharge (PD) measurement under VLF sinusoidal voltages leads to different requirements for the test system and how the results are analyzed and interpreted. This application note provides insights into how the MPD Suite software supports and simplifies a PD measurement under sinusoidal VLF test voltages.

General information

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Table of content

1	Safety instructions	4
2	Introduction.....	5
3	MPD Suite - VLF mode	7
3.1	PD charge value and dynamic weighting	8
3.2	VLF voltage measurement and synchronization	9
3.3	Display and re-export test results	10
4	Case Study #1: PD measurement and localization on a 900 m, 20 kV, XLPE cable under sinusoidal VLF test voltage.....	11
4.1	Test setup	11
4.2	Partial discharge detection sensitivity.....	12
4.3	PD fault localization methods commonly used during VLF testing	14
4.3.1	Signal propagation and attenuation on MV cable system	14
4.3.2	TDR – time domain reflectometry	14
4.3.2.1	Principle	14
4.3.2.2	How to trigger the PD scope	17
4.3.2.3	How to improve the PD scope signal quality	18
4.3.3	sTDR – statistical time domain reflectometry.....	19
4.4	Comparison of PRPD pattern at different test voltage frequencies.....	20
5	List of literature.....	21

1 Safety instructions

This Application Note may only be used in conjunction with the relevant product manuals which contain all safety instructions. The user is fully responsible for any application that makes use of OMICRON products.

Instructions are always characterized by a ► symbol, even if they are included in a safety instruction.

NOTICE

Equipment damage or loss of data possible

- ▶ Carefully read and understand the content of this Application Note as well as the manuals of the systems involved before taking them into operation.
- ▶ Please contact OMICRON support if you have any questions or doubts regarding the safety or operating instructions.
- ▶ Follow each instruction listed in the manuals, especially the safety instructions, since this is the only way to avoid the danger that can occur when working on high voltage or high current systems.
- ▶ Only use the equipment involved according to its intended purpose to guarantee safe operation.
- ▶ Existing national safety standards for accident prevention and environmental protection may supplement the equipment's manual.
- ▶ Before starting a test always check that the test signals are suitable for your system under test.

Only experienced and competent professionals that are trained for working in high voltage or high current environments may implement this Application Note. Additionally, the following qualifications are required:

- Authorized to work in environments of energy generation, transmission or distribution, and familiar with the approved operating practices in such environments.
- Familiar with the five safety rules.
- Good knowledge/proficient in working with the MPD 800 system.

2 Introduction

A very low frequency (VLF) test voltage is commonly used to perform on-site diagnostics such as dissipation factor or partial discharge (PD) measurement on medium-voltage cable systems. Commercially available VLF voltage sources have the advantage of being small and lightweight compared to most resonance test systems, as well as having the ability to control the test voltage amplitude which is essential when it comes to characterizing PD phenomena.

PD measurement on cable systems not only allows user to assess the integrity of insulation, but also to localize a potential defect which is often linked to an accessory installed on-site.

Depending on the type of defect, the test results (PRPD pattern, PD inception voltage (PDIV) and PD extinction voltage (PDEV)) at voltages of power frequency or at very low frequency may not be directly comparable [1, 2, 3]. Studies have shown that the development of electrical trees strongly depend on the frequency of the test voltage. Individual discharge events can influence the properties in the discharge branches, such as temperature, pressure and conductivity. If the pressure cannot dissipate in between consecutive PD events, it is likely that a new discharge channel/branch will develop. At lower test voltage frequencies, the pressure inside a discharge branch has a higher probability to dissipate due a typically higher time difference between consecutive pulses, leading to fewer branches and a straighter tree structure. Figure 1 highlights that an electrical tree at power frequency will look more bush-like compared to a tree developed under VLF voltage stress.

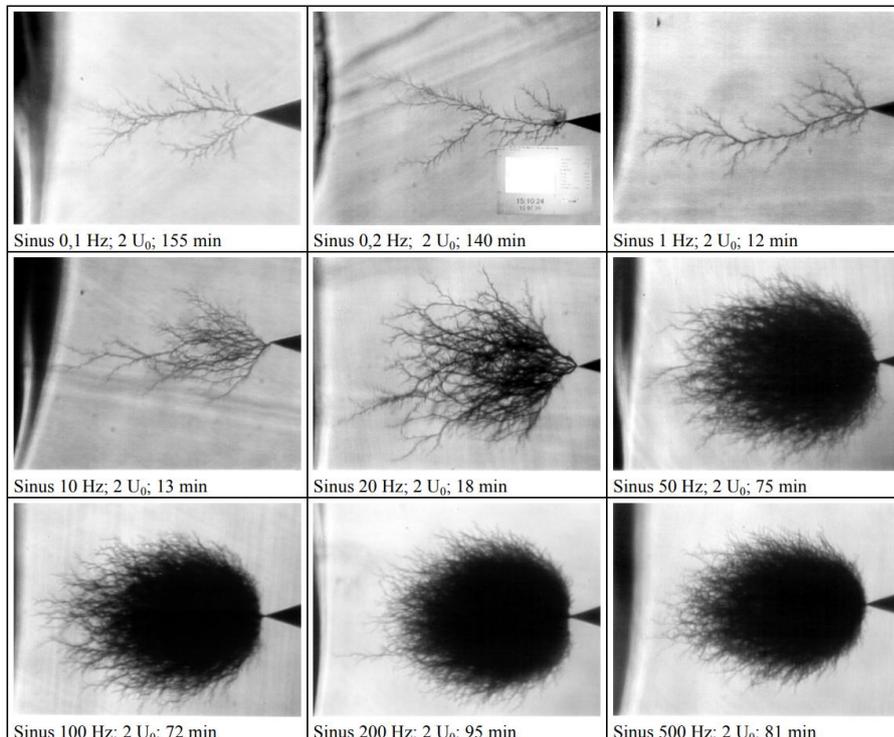


Figure 1: Growth of electrical trees in polyethylene at different test voltage frequencies and durations [3]

Sinusoidal VLF voltages are defined for a frequency range between 0.01 Hz and 1 Hz, where practical values are typical at 0.1 Hz and below. Higher VLF voltage levels might be applied to reduce the overall testing time, however the IEEE field testing guide for power cables [4] recommends a withstand test voltage for 30 - 60 min depending on the age, history and importance of the cable system.

Performing a PD measurement under VLF sinusoidal voltages leads to different requirements for the test system and how the results are analyzed. This application note describes how the MPD 800 and MPD Suite software are used to perform PD measurement and localization under sinusoidal VLF voltage stress.

3 MPD Suite - VLF mode

In the default mode, the MPD Suite software can only detect AC signals with frequencies between 5 Hz and 10 kHz. Activating the VLF mode in the VLF control panel tab extends the frequency range down to 0.01 Hz. In this mode, the MPD Suite does not automatically search for the AC frequency, instead the user must specify and enter the target voltage frequency to perform an accurate and reliable measurement.

A state-of-the-art VLF voltage source allows users to either select a fixed output frequency or use the automatic mode. The automatic mode aims for the highest output frequency for each voltage step and automatically adjusts the frequency if the power consumption reaches its limit. To ensure a stable PRPD pattern as well as charge and PD reading, it is recommended to have the same test frequency throughout the entire voltage sweep.

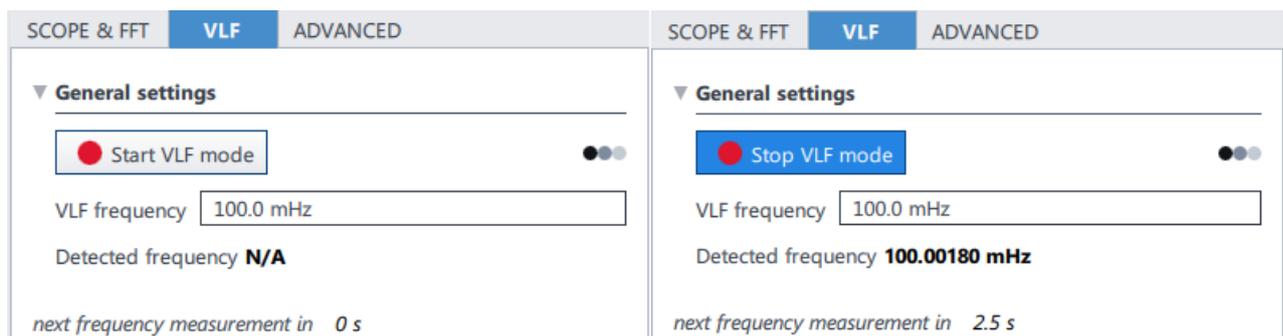


Figure 2: VLF control panel only requires two actions. Activate the VLF mode and enter the VLF target frequency.

Based on the entered frequency, the MPD Suite starts to detect the actual applied frequency which must be within 1% of the entered value to ensure an accurate voltage and current measurement.

The entered frequency also has impact on the time constant which is used by the AC and PD pre-amplifiers. A low PD repetition rate will not lead to a constantly changing gain level, even when the fully automatic AC and PD gain mode is used.

3.1 PD charge value and dynamic weighting

The apparent charge defined in the IEC 60270 [5] is a weighted value, based on the repetition rate of the recurring PD events with the highest magnitude within a certain time frame. Table 1 shows the allowed reading R of a PD measuring system depending on the PD repetition rates that are related to the absolute time and not normalized to a single test voltage cycle.

N [1/s]	1	2	5	10	50	≥100
Rmin [%]	35	55	76	85	94	95
Rmax [%]	45	65	86	95	104	105

Table 1: Pulse train response of a PD instrument according IEC 60270: 2000 + AMD1: 2015 [5]

The lower the repetition rate, the lower the corrected apparent charge value must be. As an example, the charge value of a PD event with a repetition rate of 1 pulse per second must be reduced to 40% of its original value. The above weighting table attenuates disturbance pulses with repetition rates below 50/60 Hz. For pulses with repetition rates greater to or equal to 50, the pulse is weighted with 100%. Most of the PD defects occur in one or both test voltage halfwaves ($N \geq 100$). In other words, the authors of Table 1 assume a test voltage frequency of 50/60 Hz and do not consider VLF test voltages. The scope of IEC 60270 includes alternating voltages up to 400 Hz and direct voltages. Direct voltages are specifically excluded by the above table (Note 4 of Table 1 in [5]) which does not apply for VLF.

With VLF, the AC cycle is much longer than with 50/60 Hz measurements, and thus using the table above would lead to dramatically lower PD readings for PD events recurring at every VLF cycle, severely limiting the usability and comparability of the reading.

The dynamic weighting feature is automatically activated when starting the VLF mode and adjusts Table 1 for frequencies other than 50 / 60 Hz. The actual measured AC frequency is used to derive the PD repetition rate at which down-weighting should occur. For PD that recurs with half the measured AC frequency, the charge level will be weighted down the same way as a 50 Hz PD signal would be without dynamic weighting. A PD signal with a repetition rate of 10% of the AC frequency will experience the same down weighting as a 10 Hz PD signal would see with dynamic weighting disabled. As a result, the weighted charge value does not alternate like it would when using the default Q_{IEC} weighting.

The dynamic weighting feature is a unique feature in the MPD Suite software and can be considered as being standard compliant as the weighting of pulses for VLF frequencies is implemented in the adaption of the logic of Table 1 in [5].

Statistical values such as Q_{max} over a test voltage cycle are available in the measured values overview and can be plotted in various graphs.

3.2 VLF voltage measurement and synchronization

The AC / DC setup settings within the SETUP & CALIBRATION tab need to fit the actual test setup to ensure a correct voltage and frequency measurement. For most cases a coupling capacitor in combination with the internal quadripole is used for the PD as well as VLF voltage detection. The system automatically compensates AC phase shifts based on the detected test frequency, as long as no third-party impedance is used. A Phase offset caused by a third-party impedance can be identified by a corona test and compensated with the phase offset setting. The CPL1 / 2 is not designed to measure DC or VLF signals. It is recommended to either use the internal quadripole of the MPD 800 or an external resistive divider to measure the applied test voltage equivalent.

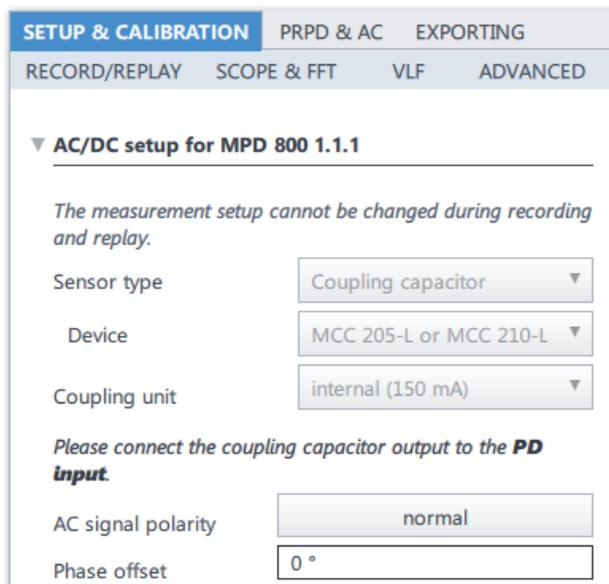


Figure 4: Settings to synchronize to the applied test voltage using a 1 nF coupling capacitor

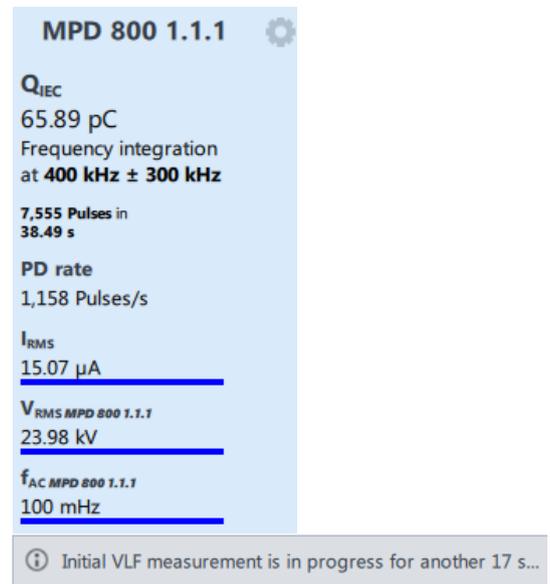


Figure 3: Progress bars indicating when the reading will be updated

500 nA is the minimum RMS signal at the PD input, that can be used to measure and synchronize to the test voltage. This current is reached at 800 V when using a 1 nF coupling capacitor and a default test voltage frequency of 0.1 Hz.

The system requires the test voltage to be applied for minimum duration of 3.5 times the AC period before it displays any readings. This ensures an accurate AC reading as well as a stable PRPD display over the entire test cycle. After the initial measurement, the readings are updated at least every 5 seconds. To get the MPD system synchronized with the applied test voltage frequency before performing test voltage sweep, it is recommended to start with a voltage level where no PD activity is expected.

The MPD Suite software provides helpful information bars and user prompts to indicate when the next VLF measurement reading is available. Figure 4 shows some examples of the VLF-related readings / messages.

3.3 Display and re-export test results

It is highly recommended to record a PD dataset (RECOPRD/REPLAY tap) for a duration which is at least as long as 15 times the period of the test voltage, e.g. for 0.1 Hz the recommended time is 150s.

The phase resolved partial discharge (PRPD) pattern displays the unweighted PD events which were detected by the MPD system with the filter settings used. The CSV export functionality within the PD/DC tab or the third-party application export (data to binary files) in the EXPORTING tab can be used to export the filtered raw data for further processing.

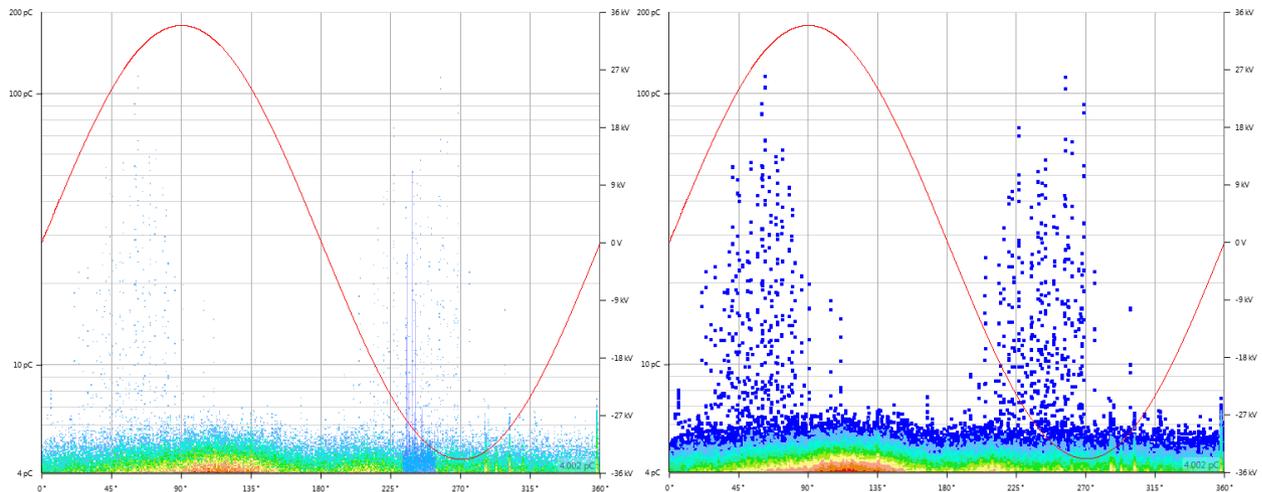


Figure 5: Left – PRPD pattern with sliding needle view of current voltage / PD stage
Right – same PRPD pattern with dithering enabled

The left part of Figure 5 shows a snapshot of the PRPD view. The events happening at the point in time are displayed as single needles within a sliding window 100 ms. This allows users to easily follow the level of the test voltage and it indicates whether or not there is PD activity.

The dithering function located in the PRPD & AC tab can be used to significantly increase the visibility of low repetitive PD events as shown in the right part of Figure 5.

Q_{max} , Q_{wtd} or Q_{avg} can be plotted in different diagrams and linked to other values, such as test voltage $Q(V)$ or time $Q(t)$.

The ASSESSTMENT tab allows for settings automated detection of PDIV and PDEV or simple pass / fail statement based on a set charge threshold(s).

Additional diagrams, such as the PD scope or the PD localization diagram, are used for fault localization and are explained in the case study.

4 Case Study #1: PD measurement and localization on a 900 m, 20 kV, XLPE cable under sinusoidal VLF test voltage

4.1 Test setup

A single-end PD measurement was performed on a NA2XS(F)2Y 1x50 RM/16 12/20kV power cable. The test voltage was generated by a commercially available VLF voltage source.

The battery powered MPD 800 PD acquisition unit is connected directly to the 1 nF coupling capacitor. The fiber optical cable ensures a galvanic-free connection between the MCU2 control unit located in the safe working area and the acquisition unit located in the HV area. The test object has a known PD source at approx. 650 m (2133 ft.) from the near end, respectively 250 m (820 ft.) from the far end.

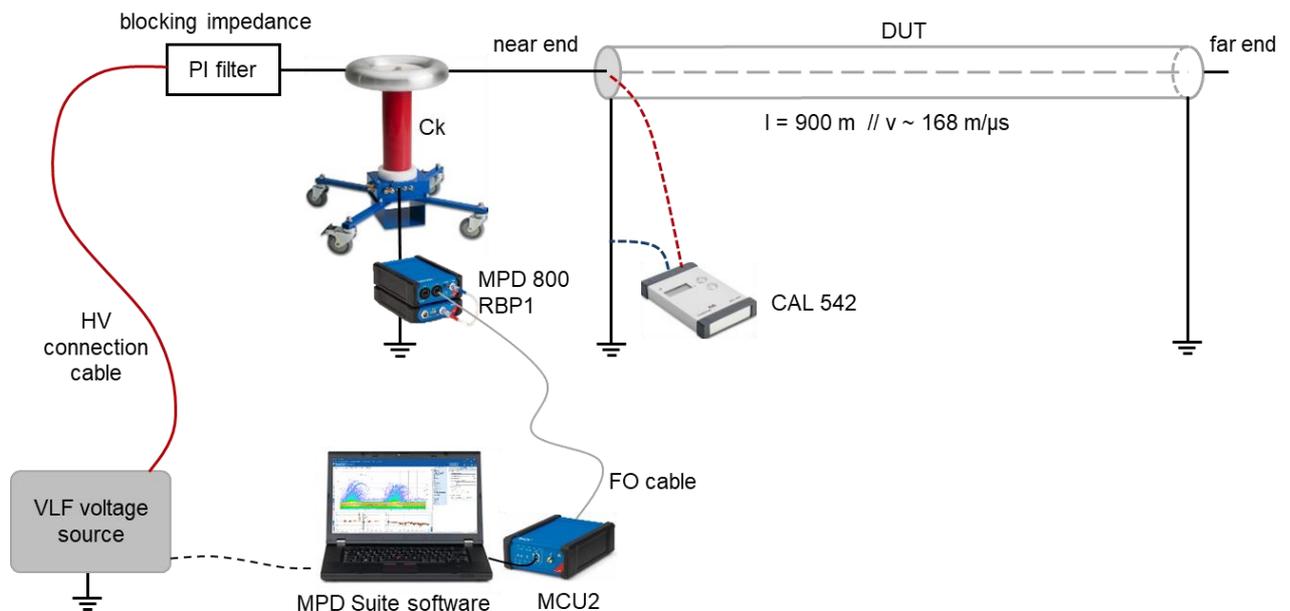


Figure 6: PD test setup for a sensitive PD detection under VLF voltage stress

4.2 Partial discharge detection sensitivity

The overall PD sensitivity in the field is often heavily influenced by external noise. The MPD 800 with its freely-selectable digital band pass filters allows a high degree of noise reduction. Cable length, wave-propagation characteristics, amount and type of joints, insulation material, mix-cable systems and obviously the ambient noise, can have significant influence on the detection sensitivity as well as localization accuracy. A detailed list of influencing factors is described in [1].

The detection sensitivity is typically expressed by the minimum apparent charge magnitude that a PD system can display when a defined charge signal in pC (charge calibrator) is injected at the far end of the cable system [1]. A calibration of the propagation speed based on the known cable length is performed using the different localization methods highlighted in the corresponding chapter.

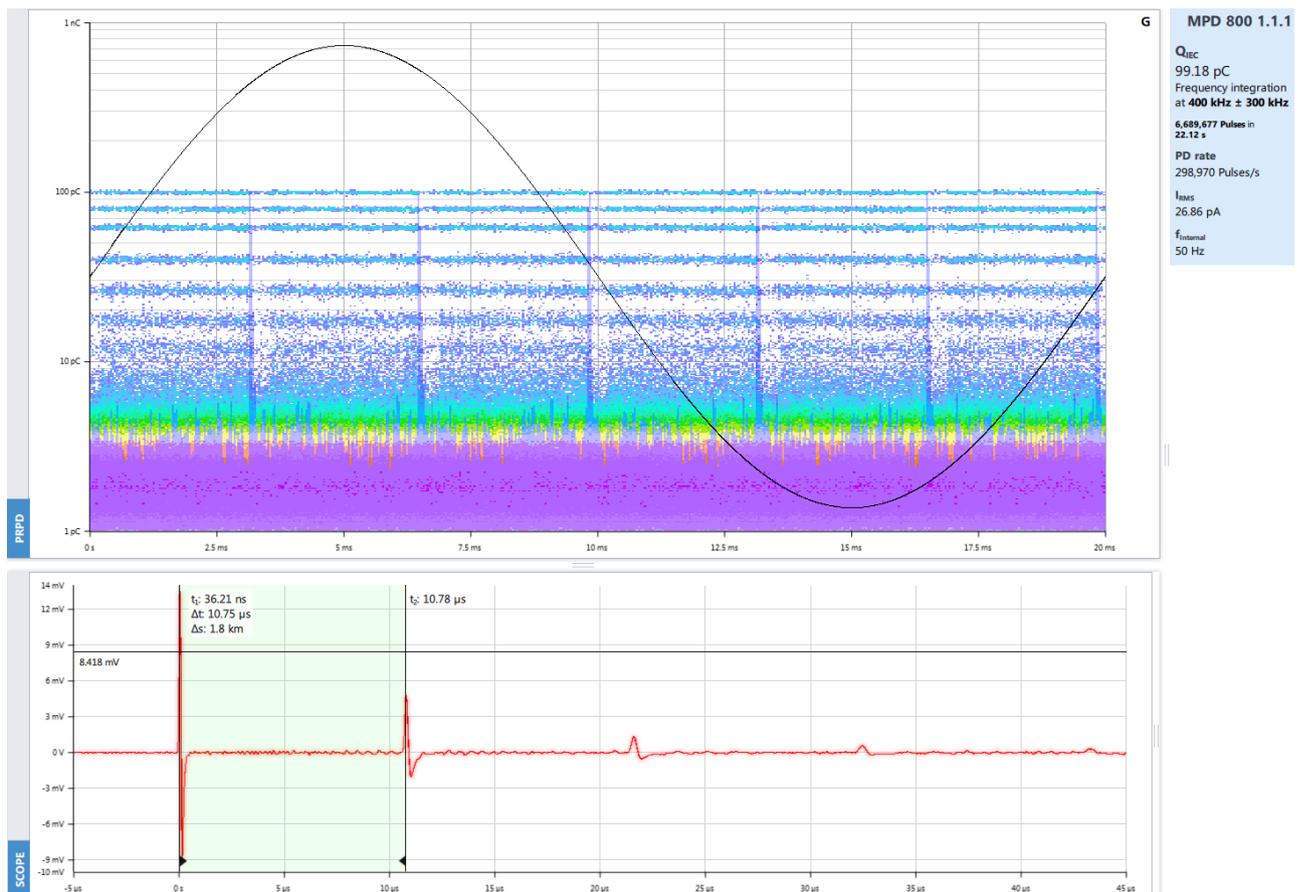


Figure 7: PD sensitivity check from the far end of the cable shows a minimum detectable charge level of ~ 2 pC

Based on Figure 7, one could assume that the detection sensitivity of the test setup is approx. 3 pC, however this is only true when the used VLF voltage source does not cause any additional noise signals, which can be more dominant than the impact of the blocking impedance. The IEEE Guide [1] highlights that some commercially available VLF voltage sources include a mechanical switch in the high-voltage circuit and thus are not PD free.

To ensure a PD free test setup, the device under test might be disconnected from the coupling capacitor and a voltage sweep performed up to the maximum test voltage. Such a setup would represent the worst-case scenario for noise emitted by the VLF voltage source as the entire high-frequency current propagates into the coupling capacitor and is not influenced / divided by the test object impedance.

Figure 8 and Figure 9 show PRPD patterns measured with VLF voltage sources from different manufacturers in a frequency range of 100 – 700 kHz. The measurement was performed with neither a device under test nor a blocking impedance. All VLF voltage sources with their connection cables, show PD-like signals which can overlap with the potential PD events occurring in the device under test.

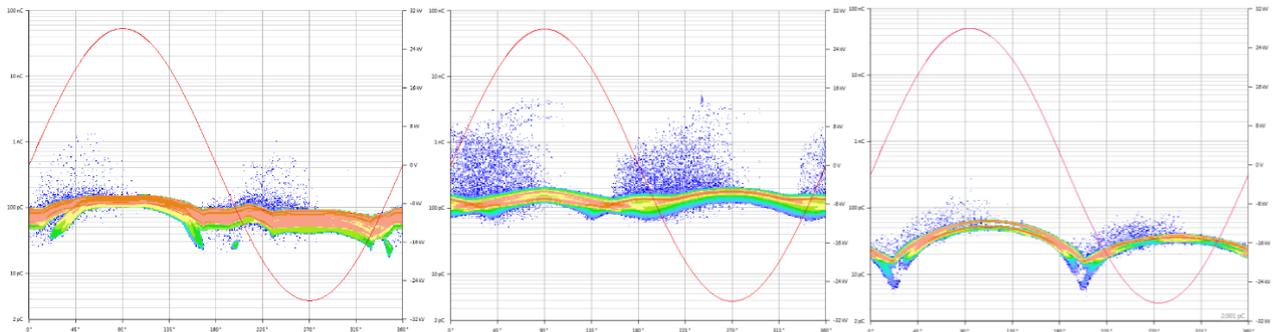


Figure 8: PRPD pattern at 20 kV / 0,1 Hz with 3 different VLF voltage sources; no blocking impedance used

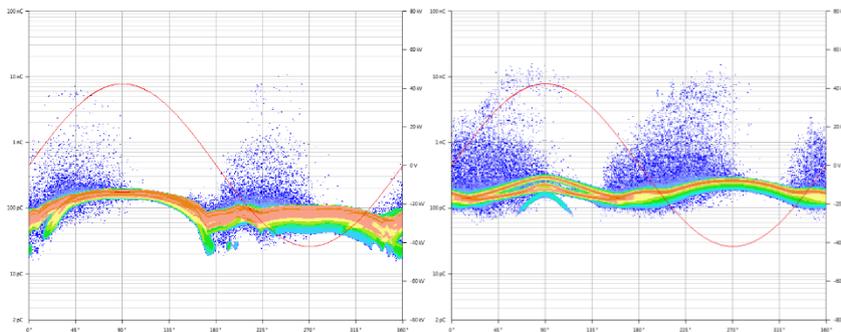


Figure 9: PRPD pattern at 30 kV / 0,1 Hz with 2 different VLF voltage sources; no blocking impedance used

The impact of the noise signals caused by the VLF voltage source on the actual PD reading depends on various factors, such as type of VLF voltage source, maximum test voltage in relation to maximum device specification and measuring frequency as well as the influence of the connected load. The examples in Figure 9 show that without the usage of a high-voltage filter, disturbance patterns of several 100 pC or a few nC are present and significantly reduce the sensitivity for the PD measurement.

To ensure a sensitive PD measurement, it is highly recommended, or possibly even required, to use a proper blocking impedance. Such a filter not only limits the high frequency noise from the VLF voltage source to be measured by the PD detector, but it also ensures a defined recharging loop. Only currents that will be recharged by the coupling capacitor will be measured, which will result in a higher sensitivity.

4.3 PD fault localization methods commonly used during VLF testing

The MPD system supports four methods to perform a fault localization on a power cable system. Highest accuracy can be achieved by a distributed PD measurement using the time-of-flight or statistical time-of-flight methods between two or more detection points.

For onsite medium-voltage cable PD measurements, where VLF test voltages are used, the setup typically consists of a single-end measurement. Therefore, often the basic time domain reflectometry and the more advanced statistical time domain reflectometry are used. Additional information about distributed PD measurements and localization can be found in the application note [6].

4.3.1 Signal propagation and attenuation on MV cable systems

A PD event occurring in the insulation of a cable or cable accessory will lead to an induced current on the inner and outer conductor of the cable and will propagate in both directions. At the point of the origin, these signals can contain frequencies up to several tens or even hundreds of megahertz. The frequency content at the point of measurement can be strongly reduced and influenced by attenuation and dispersion as well as by the transmission and reflection at an impedance change, such as transition from cable impedance to joint impedance. The real signal distribution in a medium-voltage cable system can be very complex, especially when mixed insulation systems (extruded and laminated cables) are used. A charge calibrator can be used to potentially detect expected reflection points.

A sensitive measurement on the entire cable length can typically be achieved by selecting the measurement frequency as low as possible, but as high as needed to avoid excessive noise which might be present at lower frequencies.

4.3.2 TDR – time domain reflectometry

Time domain reflectometry is typically used to localize PD activity as well as to identify the reflection points and propagation speed during the PD (length) calibration.

4.3.2.1 Principle

Figure 10 to 13 represent the basic TDR working principle as well as the signal distribution on a cable system with limited or no impact of signal reflection at joints, attenuation and dispersion.

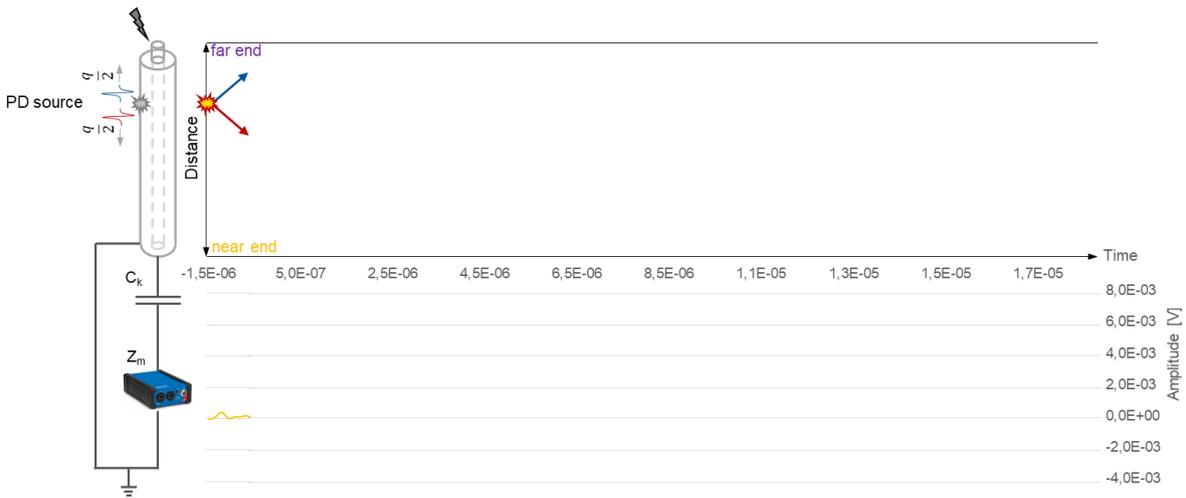


Figure 10: PD event occurring in a cable system will lead to an impulse propagating in both directions of the cable

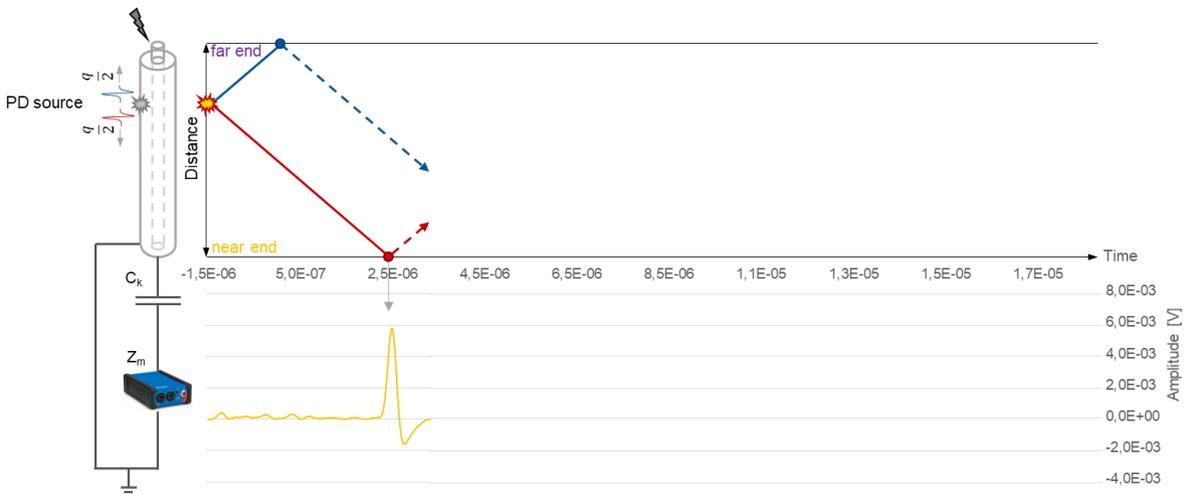


Figure 11: Signals will be reflected at impedance changes, such as the transition from cable impedance to joint impedance or at cable terminations.

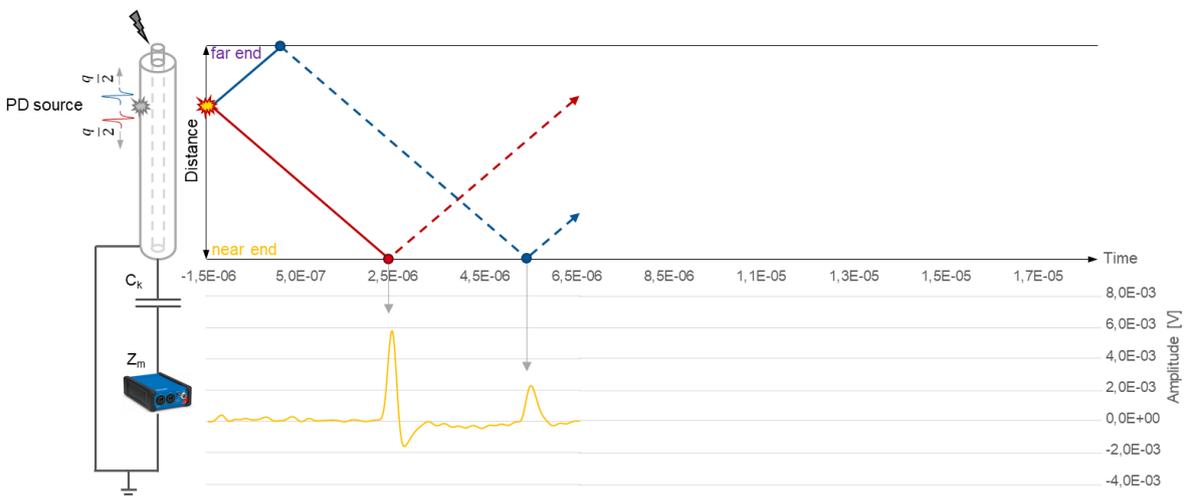


Figure 12: The PD scope shows the direct as well as reflected pulse detected at the near end of the system.

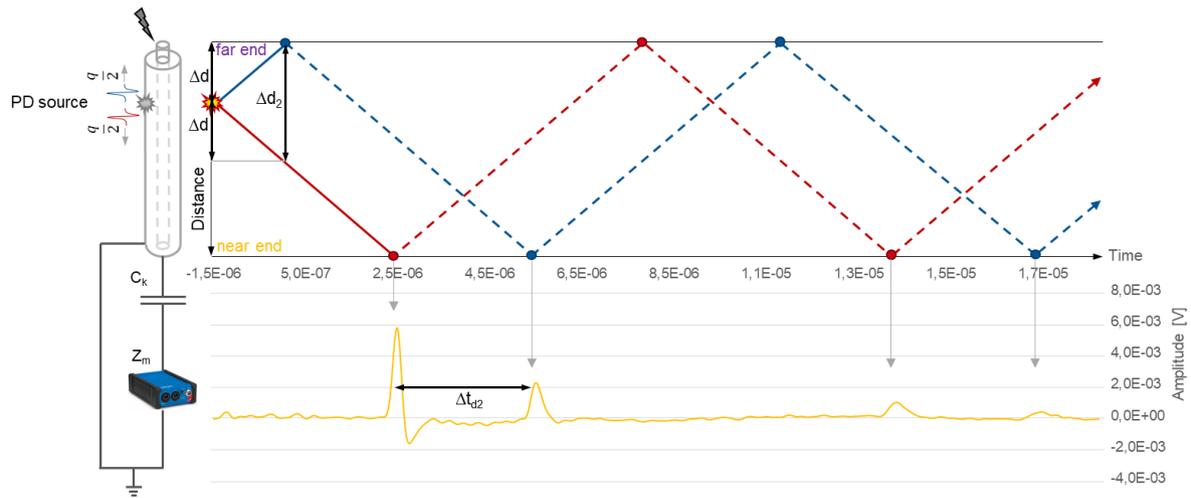


Figure 13: The time difference between detected impulses can be used to calculate the fault location with respect to the near end or with respect to the reflection point which is often the far end.

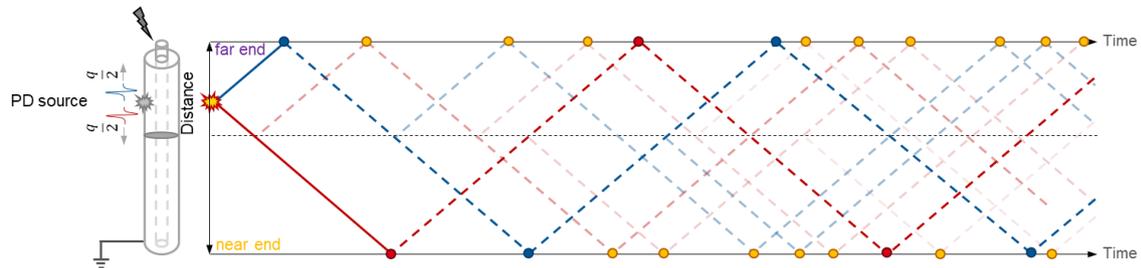


Figure 14: The type of joint can have significant impact on the complexity of the diagram.

4.3.2.2 How to trigger the PD scope

The PD scope is updated every 41 ms and represents the time signal at the input of the MPD 800 unit measured with a 35 MHz bandwidth. It can be used for PD fault localization (TDR, ToF) as well as analyzing disturbances in the linked frequency spectrum (FFT). It supports various trigger methods, such as auto trigger, peak or edge trigger, as well as a highly advanced and selective PD event trigger window. The PD event trigger allows users to select areas in the filtered PRPD view. Only impulses within the selected area and the proper impulse polarity will lead to a trigger condition for the unfiltered PD scope. Figure 12 shows the PD Event trigger applied during a VLF measurement to positive as well as negative discharge events. Multiple PD faults can be localized with this trigger method if they can be identified as individual defects in the PRPD view. Changing the measuring frequency can improve the ability to separate different PD / noise signals.

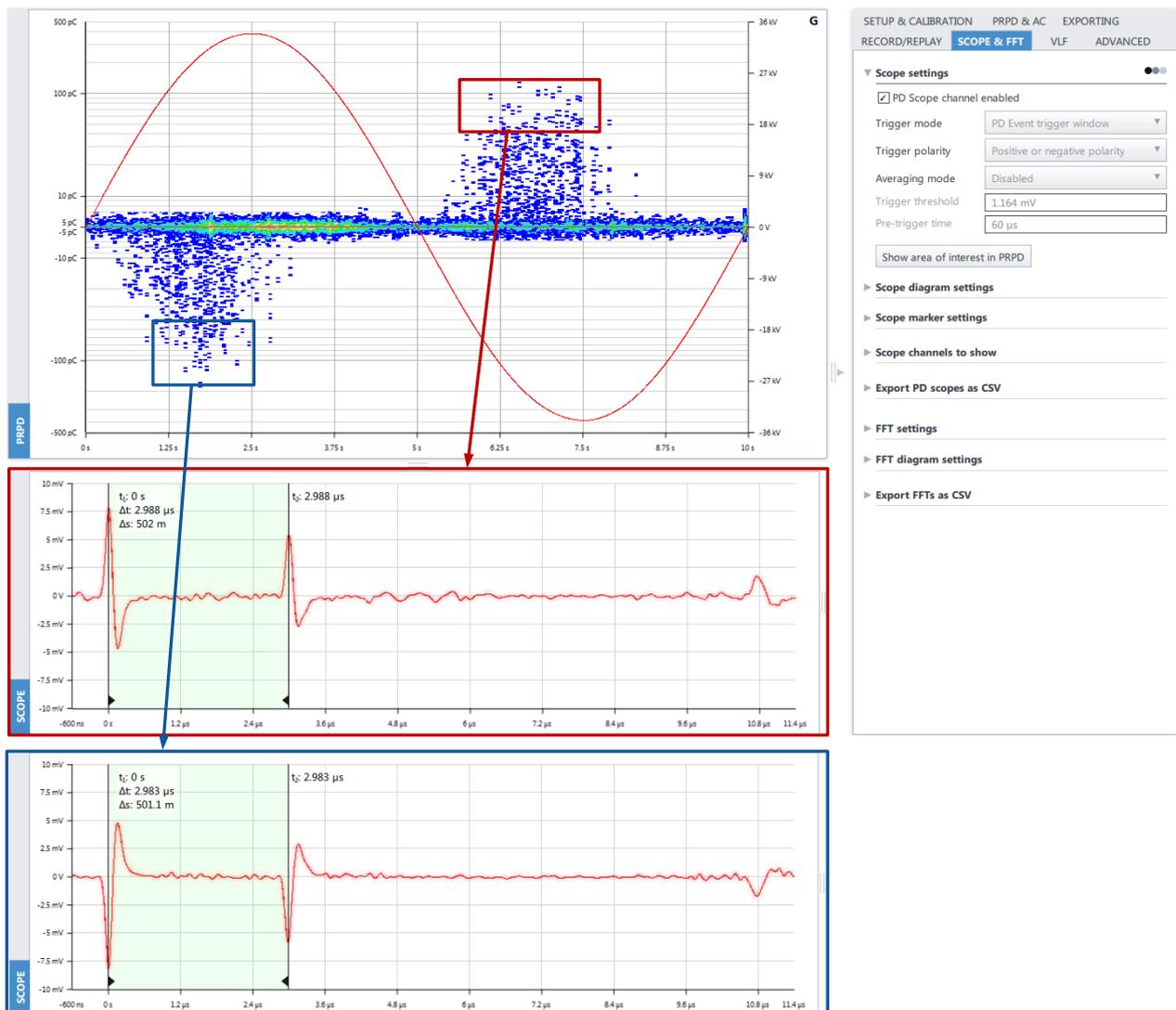


Figure 15: PD Event trigger window used to trigger the PD scope; fault location from near end is 900 m – 251 m = 649 m

4.3.2.3 How to improve the PD scope signal quality

Activating the digital low pass filters in the ADVANCED tab can improve the quality of the signal in time domain, especially in case of external disturbances above the selected cut-off frequency. Figure 13 shows the time signal of the same discharge event with different low pass filters applied. Averaging multiple scope signals within the SCOPE & FFT tab can additionally improve the signal quality if triggered on the same source.

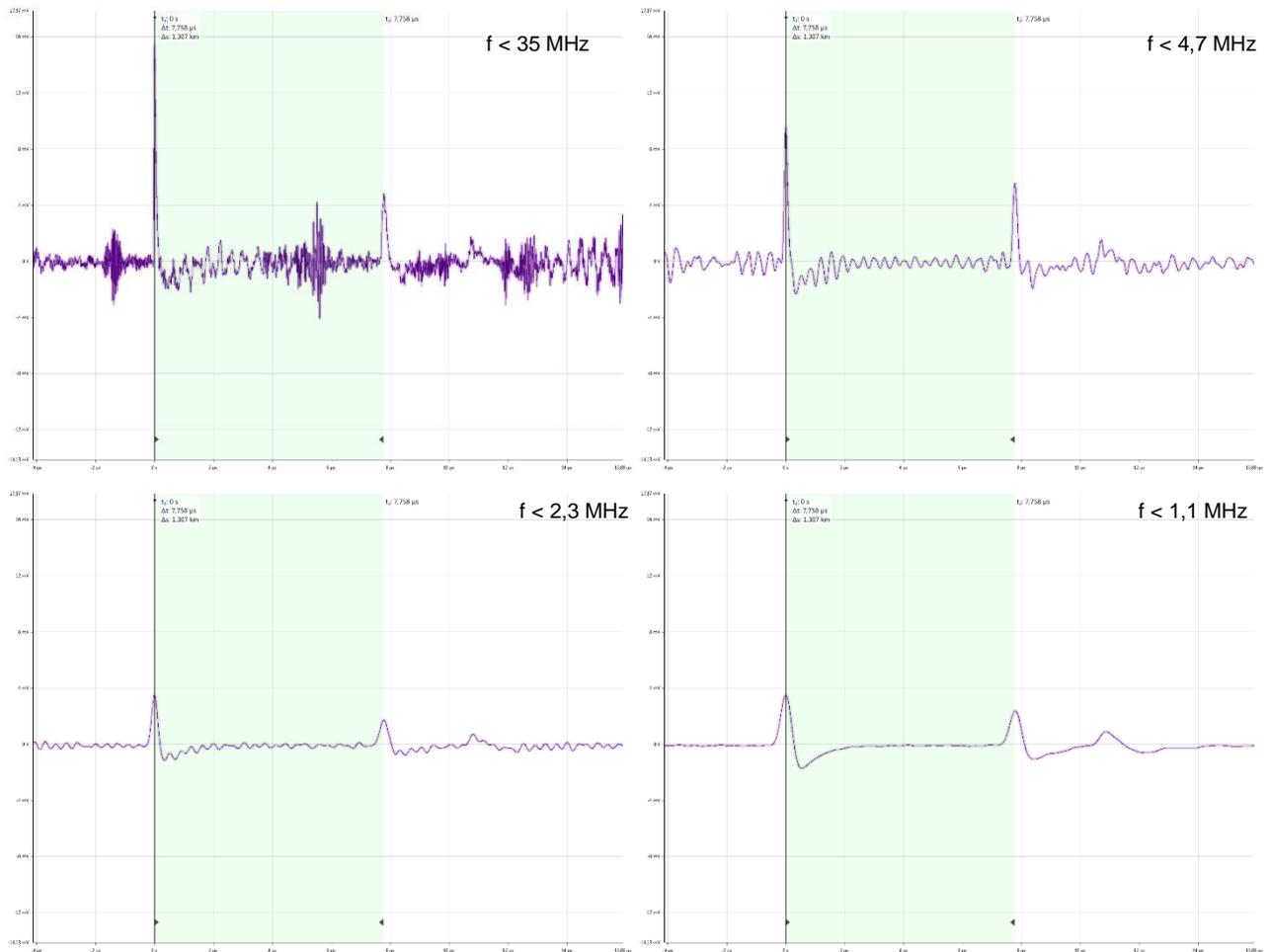


Figure 16: Impact of digital low pass filters on signal quality.

4.3.3 sTDR – statistical time domain reflectometry

Statistical TDR utilizes the filtered PD events after the bandpass filter has been applied. This has the advantage that the reflected impulse can be measured even when hidden in the ambient noise level. A PD event along a cable system will always lead to a defined and constant propagation time – the statistical approach allows users to detect these time stamps. The user can select an area in the PRPD view, which is similar to the PD event trigger window. Events occurring in the selection will be correlated with all other filtered impulses for the period of the correlation time. The entered cable properties (propagation speed and cable length) are used to calculate the maximum signal propagation time, which automatically defines the correlation time.

The PD LOCALIZATION diagram shows the amplitude and time correlation of the selected events with all other events within the correlation time. It is automatically scaled to the entered cable length which is highlighted with a light grey bar. The dark grey area in the diagram represents the dead time of the PD band pass filter used. PD events occurring within a short time difference, such as a fault close to the far end of the cable, can only be identified as two consecutive impulses if the filter dead time is smaller than the time difference between the consecutive pulses. The dark grey area represents a blind spot where no localization can be performed. The dead time of the selected filter is shown in the ADVANCED tab and is indirectly proportional to the filter bandwidth. A wideband filter is beneficial and leads to a small filter dead time. Additionally, the filter dead time needs to be considered for signals occurring at the near end, as it adds an additional localization error as two pulses (reflection and 2 times cable length) might merge. Figure 17 shows the selection in the PRPD view and the correlation in the PD LOCALIZATION diagram / tab based on the entered cable settings (900 m, 168 m/μs). The MPD Suite shows the fault location with respect to the distance to the MPD 800 measurement location

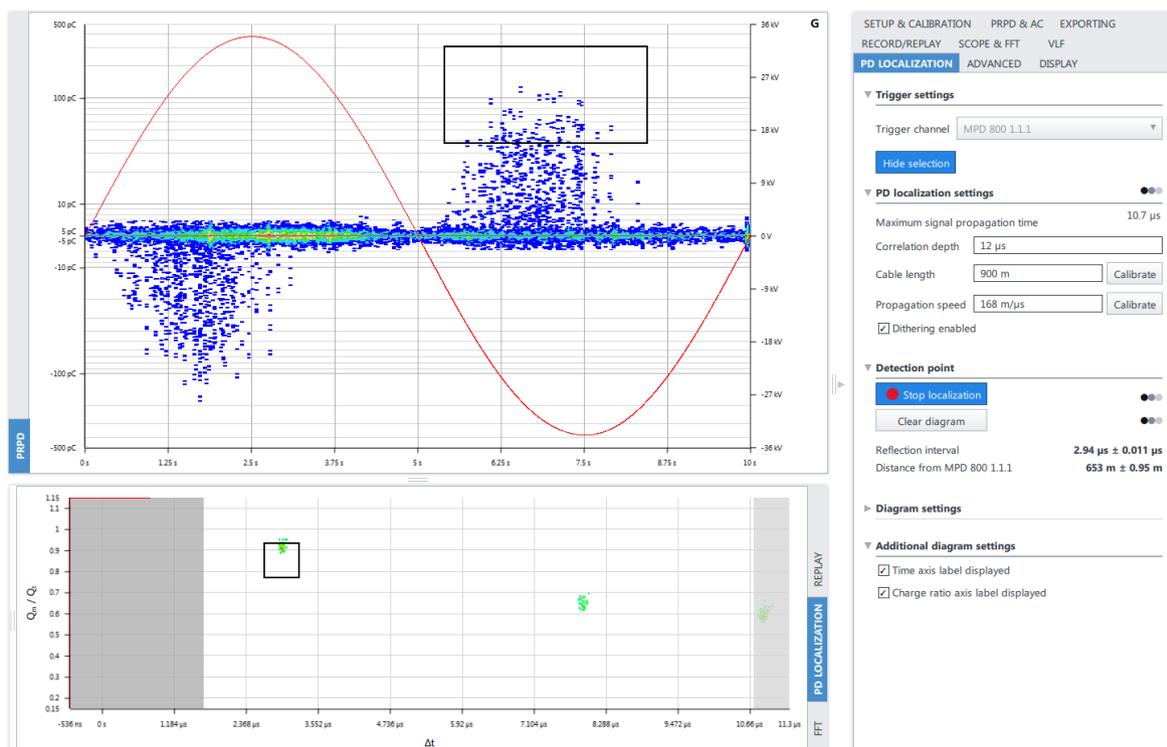


Figure 17: sTDR fault localization on a 900 m power cable; fault location is 653 ± 0.95 m seen from the MPD measurement device.

4.4 Comparison of PRPD pattern at different test voltage frequencies

Figure 18 shows the PRPD pattern of a cavity below the stress control tube of a medium-voltage cable joint at different test voltage frequencies. All patterns are recorded over an interval of 39 test voltage cycles. The repetition rate of the given fault strongly depends on the VLF voltage frequency. The overview indicates that the shape of the pattern gets distorted with decreasing output frequency but remains similar to some degree.

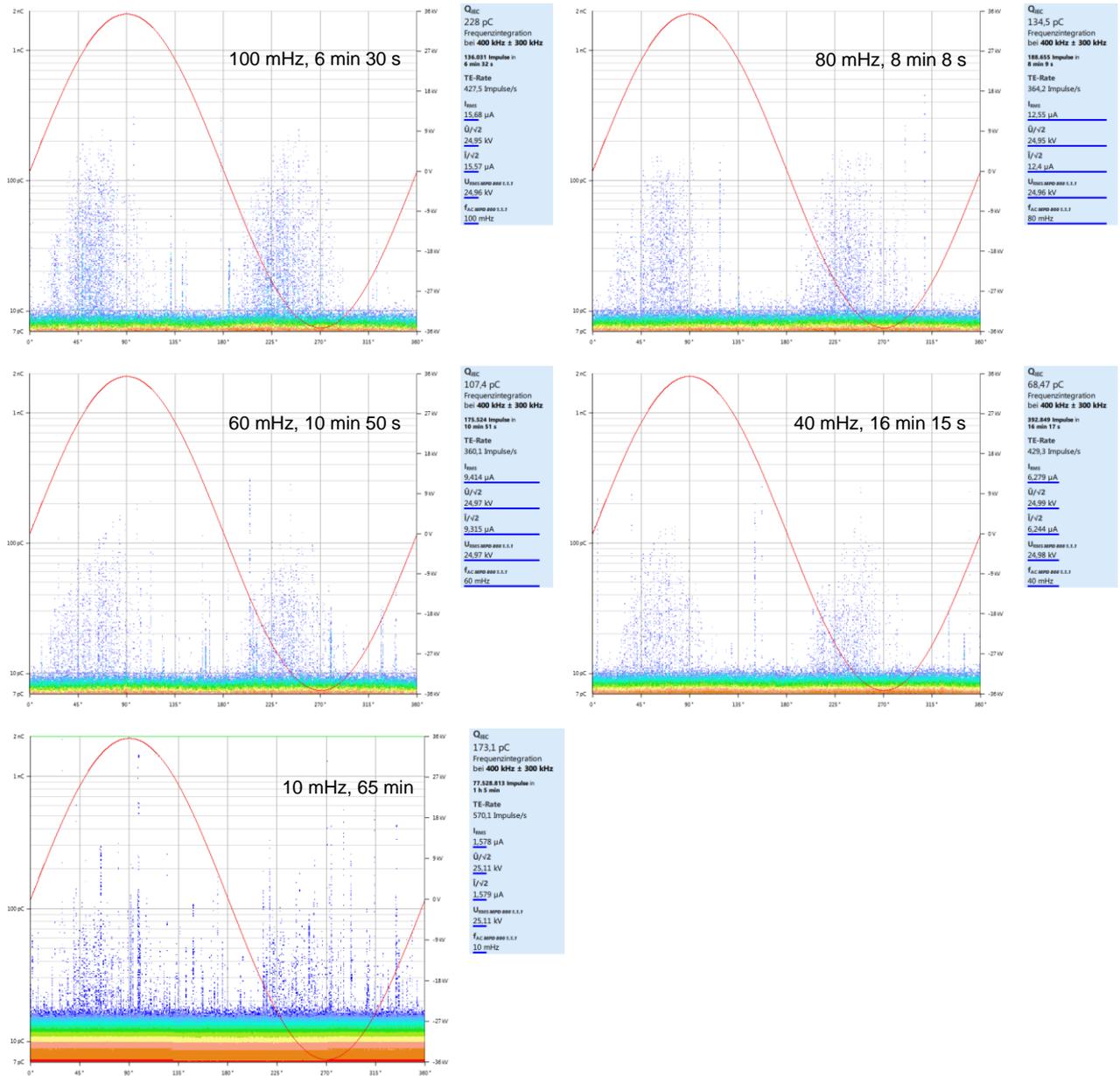


Figure 18: Comparison of internal PD fault at different VLF test voltage frequencies

5 List of literature

- [1] IEEE Std. 400.3-2006: "IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment"
- [2] E.Ildstad / F. Mauseth: "Voltage and Frequency Dependence of Electrical Treeing in XLPE Cable Insulation", Nordic Insulation Symposium 2009
- [3] D. Pepper: "Grundlagenuntersuchung zum Teilentladungsverhalten in kunststoffisolierten Mittelspannungskabeln bei Prüfspannungen mit variabler Frequenz und Kurvenform"
- [4] IEEE Std 400.2-2004: "IEEE Guide for Field Testing of Shielded Power Cable Systems Using Very Low Frequency (VLF)", New York, USA, 2005
- [5] IEC 60270: "High-voltage test techniques – Partial discharge measurement", Version 2000, 3rd Edition
- [6] OMICRON application note: Distributed partial discharge measurement and localization using GPS synchronized datasets

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