Long lengths transmission power cables on-site testing up to 500 kV by damped AC voltages

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ABSTRACT

Since 2004 damped AC (DAC) voltages are in use for on-site testing and diagnosis of (E) HV cables. DAC testing is an alternative method to conventional ACRTS testing and has got worldwide at several utilities and service providers its acceptance for:

- *quality control of cable and accessories installation during after-laying testing,*
- *maintenance testing during operation or in conjunction with repair work after a failure,*
- *condition assessment of service aged cable circuits,*

In this contribution the newest mobile solutions for DAC field testing up to 500 kV of cable lengths up to 25 - 40 km will be presented. As an innovation to the existing single side (E)HV DAC systems for energizing long lengths and for PD detection on longer cable lengths compact high power sources with an additional range extension solution will be presented.

INTRODUCTION

After-laying tests of new installed and diagnostic testing of service aged transmission power cables are an important issue to obtain knowledge about the actual condition of the complete cable system and to prevent breakdowns during service. The application of damped AC (DAC) voltages including standardized conventional PD detection and analysis is world-wide accepted for on-site testing and diagnosis of (E) HV power cables [2-12]. This technology is based on the off-line energizing of a cable section with the possibility of testing with elevated voltages.

	ACRT	DAC
Max output voltage [kVrms]	160	191
Max test capacitance @ Umax [uF]	1.6	27
Min test capacitance [nF]	17	15
Frequency range at Umax [Hz]	30-300	10-800
Max. input power demand [kVA]	100	4.5
Transport	heavy truck with trailer (excluding generator)	small van
Total weight [kg]	26000	1050
Transport volume [m3]	67	9
Integrated dissipation factor (tan δ) measurement	No	Yes
Sensitive IEC 60270 PD measurement possible	No	Yes
PD detection integrated	No	Yes
PD localization	terminations and cross-bonding joints only	terminations, all joint types and cable insulation

Table 1: Example of a comparison of ACRT system characteristics to those of a DAC system.

In contrast to existing multi units ACRT solutions the damped AC technology makes it possible using one single unit to energize long lengths of power cable with a high capacitance with a low input power demand [1]. In table 1 an example of a comparison is shown.

In addition to the PD inception equivalence of sinusoidal damped AC voltages (in the frequency range of 20-300Hz) compared to the 50/60 Hz network stresses the characteristics of the applied technology meets the specification of an on-site testing system:

- Lightweight modular system,
- Compactness in relation to the output voltage,
- Low effort for system assembling,
- Low power demand, even for long cable lengths,
- Low level noises and possibility of sensitive PD detection and dissipation factor measurements.

Onsite testing with damped AC voltages makes is possible to include IEC60270 standardized PD detection method, see Fig. 1. There are different parameters which can influence the quality of the partial discharge measurement [12-23]. Especially in the case of long length power cable systems, the PD detection sensitivity is a known issue that can be challenging. Also the PD origin localization in long cable lengths can become more complicated compared to shorter cable lengths. Due to limited sensitivity, which is affected by the noise level at on-site situations, the detectable PD magnitude is an important factor for each PD test.
To localize the origin of PD, a common used method is the time domain reflectometry (TDR). Using this technique, a detectable reflection of the PD pulse from the far end of the cable has to be detected by the measurement device.

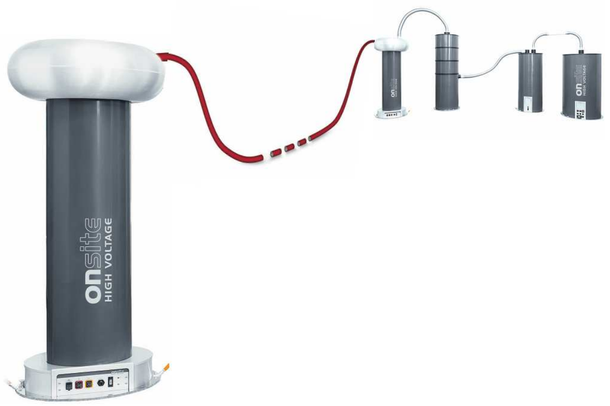

Fig. 1: Example of a 300 kV DAC test system with double side PD testing and diagnosis extender for long transmission cable circuits

The PD measurement sensitivity and localization chance can be extended by using an additional PD measuring system at the second (far) end of the cable. This unit measures PD activity with the conventional standardized PD detection synchronized with the damped AC test voltage and synchronized with the PD measurement at the near end of the cable. This two sided measurement provides higher detection sensitivity, especially in the case of long cable lengths. This technique provides more precise PD measurements and enhances the possibility of localization of the PD origin in power cables.

In this contribution the newest mobile solutions for DAC field testing applicable up to 500 kV cables with lengths up to 25 - 40 km will be presented. As an innovation to the existing single side (E) HV DAC systems for energizing long lengths and for PD detection on longer cable lengths compact high power sources available up to 500 kV with an additional range extension solution will be presented, see Figure 1.

SINGLE SIDED MEASUREMENT AND PD ORIGIN LOCALIZATION

The classical single sided measurement technique uses one PD detection circuit. A schematic setup is shown in Fig. , which contains the PD detector, a coupling capacitor and the cable. On the left side of the cable, the inner conductor of the cable is connected to the coupling capacitor and the DAC system. The far end of the cable has an open end. Fig. shows a typical setup for energizing and single side measurement of PD in a power cable.

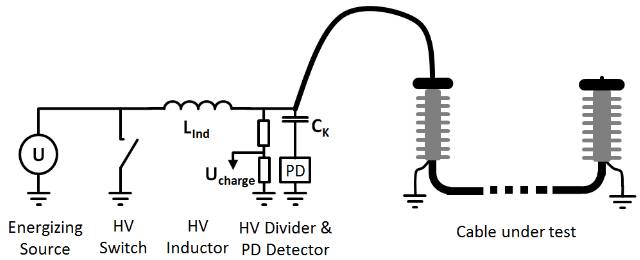

Fig. 2. Measurement setup for single sided PD measurement with DAC voltage excitation and PD detection circuit.

The DAC excitation unit exists of an energizing source, which energizes the cable circuit over the resonance inductance Lind. After reaching the desired test voltage, the resonant circuit will be closed over the HV switch. The resistive HV divider measures the damped sinusoidal voltage. Simultaneously the PD detector circuit records the partial discharge activity in the cable.

At the fault location, every partial discharge displaces a small amount of electric charge. This process emits two impulses in the cable, one into each direction away from the fault origin. These pulses are propagating through the cable, Fig. 3. At the moment t_A the detector recognizes the first pulse, which is travelled directly from the PD origin to near end of the cable. A second pulse t_B can be measured with a time difference Δt. This pulse travelled from the PD location to the far end, is reflected, travel's in the other direction to the near end and can be measured a certain time later. This time difference Δt is crucial for localizing the PD origin.

To calculate the distance X_{PD} between the measurement device and the PD origin, equation (1) is used, where L_{cable} is the overall length of the cable and v the propagation speed which is dependent on the cable characteristics.

$$X_{PD} = L_{cable} - \Delta t \cdot v/2 \qquad (1)$$

Especially in noisy environments or with long lengths of cable this technique has limitations in locating the PD origin. In particular the reflected pulse at the far end has a longer distance to travel before reaching the measurement device. This results in a higher attenuation and consequently decreasing pulse amplitude. Depending on the specific cable characteristics there is a limitation for the localization of the PD origin with increasing cable length. The sensitivity of the PD localization decreases also with the environmental noise. Disturbances can occur even if the cable system is not energized. This sensitivity also depends on the used PD detector measuring range.

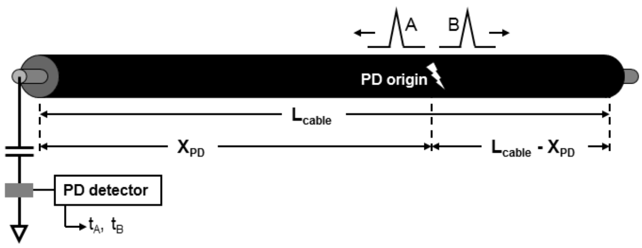

Fig. 3. Power cable with PD source emits two travelling waves A and B with speed v. The PD detector on the left side can calculate the PD origin with the aid of TDR analysis.

This TDR technique is based on the reflection of the PD pulse at the cable end. It can be possible, that the reflected pulse is not detectable anymore at the left side, where the PD detector is placed. To overcome this problem, the double sided measurement can be performed. This technique increases the detection distance in which the PD origin localization is possible.

DOUBLE SIDED MEASUREMENT

Detection and localization of PD in cable system with long length can be improved by performing PD measurements at both sides of the cable circuit [3]. This will for the worst case situation (PD at the near end) reduce the travelling distance for PD pulses by a factor 2. In single side measurement setup, a near end partial discharge has to travel through the whole cable length to the far end and the whole cable length back to the near end. The overall travelling distance is therefore two times the cable length. In double side measurement the near end PD only has to travel to the far end to be detected there, so only one time the cable length. For this double sided measurement system a damped AC system for energizing the cable system is used, see Fig. . This system uses a coupling capacitor with PD detector A on the left side and a PD detector B at the right side.

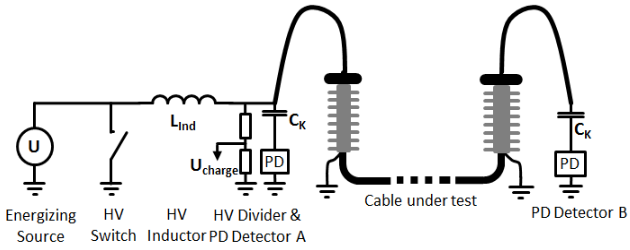

Fig. 4:Setup for two sided PD measurement with localization feasibility. DAC excitation circuit and synchronized PD detector units.

Basic setup

On both sides of the cable system, PD detectors are installed. The detectors have to be synchronized to correlate the measurement data of both sides. Fig. 4 shows the principle setup and the distances used for the calculation of PD origin. The overall length L_{cable} of the cable system is divided into two parts, the distance from the left side to the PD origin X_A, and the distance X_B from PD origin to the right side cable end, Fig. 5.

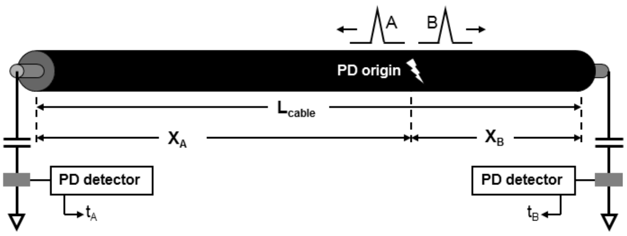

Fig. 5: Setup for the double sided PD measurement with fault localization functionality. tA and tB are the times were the direct travelled partial discharge waves are measured. Both PD detectors have to be synchronized for PD origin localization.

Localization functionality

Both measurement units record data during the DAC voltage excitation. Therefore the measurement settings and the measurement data are communicated between the two measurement units. Furthermore the units are time synchronized to obtain phase resolved PD patterns at both sides as well a synchronized localization analysis.

$$X_{PD} = L_{cable}/2 - \Delta t \cdot v/2 \qquad (2)$$

To calculate the PD origin, equation (2) can be used. As in the chapter before, the distance X_{PD}, is the distance from the left detection unit to the PD origin and Δt the time difference of t_2 and t_1.
In this particular configuration the PD pulses are directly measured and there is no need to take reflections as is the case with the single sided TDR evaluation. As both units are synchronized, the difference in the arrival times of the pulses at both sides together with the pulse velocity obtained from the calibration provides the location of the discharging defect.

Advantages of the double sided PD measurement

The main advantage of the double sided measurement is the better sensitivity compared to the single sided measurement. The PD pulses have to propagate only to the ends of the cable. No reflection at the far end is necessary. As a result there is no additional attenuation due to imperfect reflection or attenuation for travelling through the whole cable once again.
The attenuation decreases the amplitude of measureable partial discharge pulses. This attenuation can be described with an exponential function, with two constants c_0 and c_1 in the exponent. Equation (3) describes this amplitude decreasing, with PD_0 as initial PD amplitude and x the variable of the travelled length.

$$a_{PD} = PD_0 \cdot \exp\left(-x \cdot \left(\frac{1}{c_0} + \frac{1}{1+c_1}\right)\right) \qquad (3)$$

As can be seen from Fig. 6 and Fig. 7 the double sided measurement results in a higher sensitivity of the PD detection than the single sided measurement. As an example a long cable is simulated with single and double sided measurements. For the single sided measurement, normalized PD amplitude of 100 percent for the near end pulse and a reflected pulse of about 4 percent could be detected. With a double sided measurement setup, the remaining PD amplitude on the right side is about 19 percent.

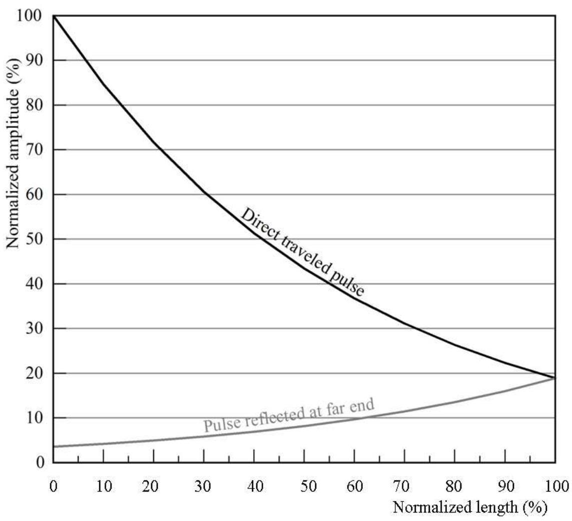

Fig. 6: Normalized PD amplitude attenuation on both sides of a long cable for double sided measurement (black). The reflection for the single sided measurement is the grey curve.

In the case of a fault location between both ends, an example is taken of a PD origin at 20% seen from the left side, shown in Fig 7. Due to the attenuation, the decreasing PD amplitude has about 70 percent of the original amplitude. In a single side measurement setup the reflected pulse over the far end decreases to 5 percent. A double sided measurement increases the remaining PD amplitude to about 26 percent.

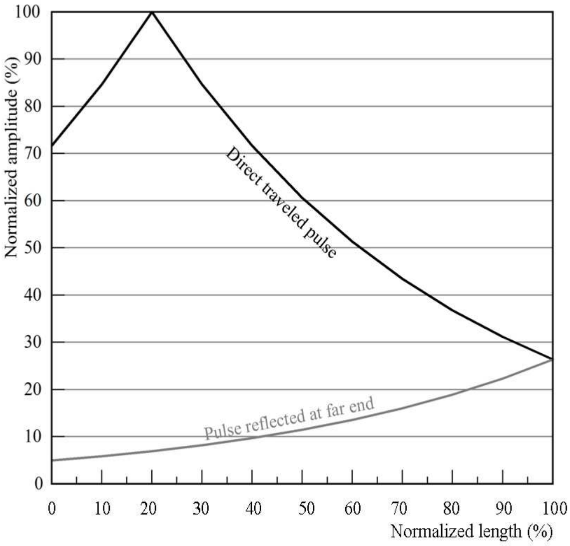

Fig. 7: Normalized PD amplitude attenuation with a fault location at 20% seen from the left side. The reflection on the right side is coloured in grey.

Fig. 6 and Fig. 7 show the improvement of the sensitivity with the double sided measurement. The worst case for localization is a PD fault location at the cable end. In such a situation, the PD pulse attenuation is the highest, due to a travelling distance of the whole cable length.
The double sided measurement brings advantages in detecting sensitivity and localization possibilities of PD pulses on long cable lengths. Due to the use of two PD measurement units, the hardware is more complex, than compared to the single side measurement. In particular the synchronization and data transmission over long distances is a challenge.

EXAMPLES

Typical measurement data used for time domain reflectometry

For partial discharges occurring at the near cable end, where in case of a single sided measurement the PD detector is located, the first measurable pulse appears with a fast rise time and high amplitude compared to its reflection. The second detectable pulse is time delayed with two times the cable travelling time with the specific wave propagation velocity.

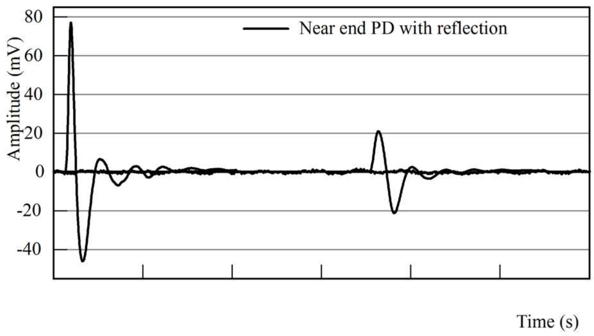

Fig. 8: Near end PD fault location with reflection from the cable far end.

In Fig. 8 the PD is located at the near end. After the detection of the first pulse the reflection occurs in the graph after a number of µs. The amplitude decreased due to attenuation while travelling through the cable. Also the rise time is slower than compared to the first direct measured pulse.

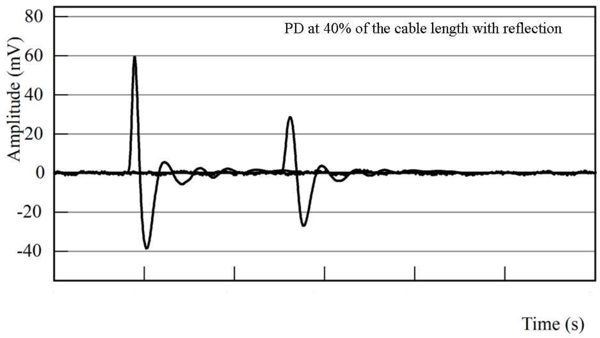

Fig. 9: PD fault location 40% cable length from the PD detector with reflection from cable far end.

Fig. 9 shows the TDR measurement for a PD pulse origin located 40% of the cable length away from the PD detector. The first pulse detected travelled the direct distance between the PD location and the PD detector. The reflection of the PD pulse arrives with a delay. With the information of this time delay, the PD origin can be calculated.
The first pulse in Fig. 9 has higher amplitude than its reflection, which has the same behaviour as in the near end case. Different in this case is that the rise time of both pulses is reduced, due to travelling along the cable for a not negligible distance.

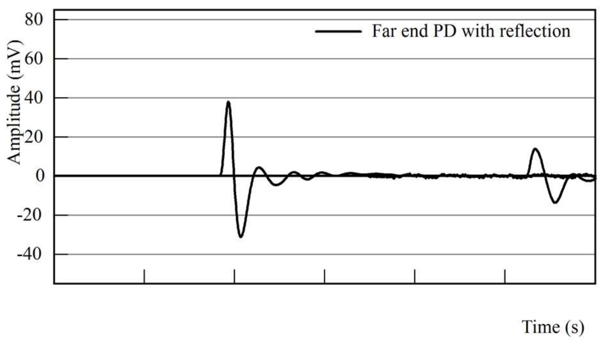

Fig. 10: PD fault location at the far end from PD detector and reflection over near and far end.

In Fig. 10 a measurement example for the far end PD is shown. In this case both PD pulse amplitudes are already decreased due to the attenuation. The rise time of the first pulse is not much faster than the rise time of the reflected pulse.

Double sided PD measurement

This example shows a synchronized and combined double sided measurement. The measured data from each PD detector from the left and right side are plotted in one graph.

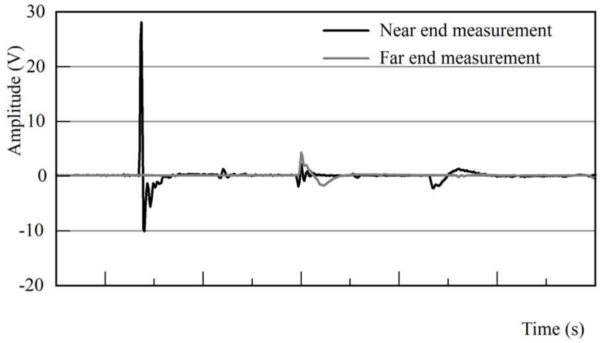

Fig. 11: Double sided PD measurement data. Detector A is located at the near end side of the cable and Detector B on the opposite far end side. The PD pulses are injected at the near end close to Detector A.

Measured data from detector A is coloured in black and the data from detector B in grey. The measurement in Fig.11 shows a PD origin on the near end, located to detector A. After one cable travelling time the pulse reaches detector B. Some µs later the reflection over the far end is detectable at detector A. This pulse is attenuated due to a travelling length of two times the cable length.

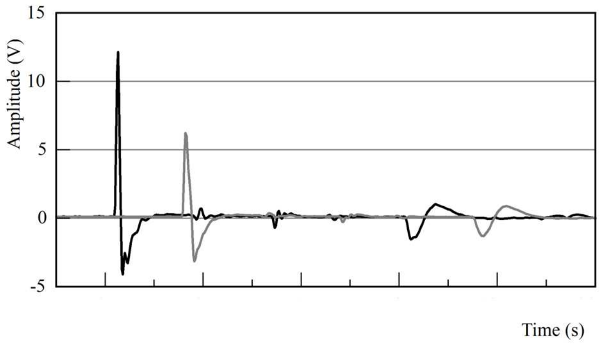

Fig. 12: Double sided PD measurement data with PD origin at the position of 40% of cable length from Detector A and at the position of 60% of cable length from Detector B.

The data in Fig. 12 is measured in the same way as in Fig. 11, with detector A on the one side, and detector B on the opposite side. The PD pulses are generated 40% of the cable length from detector A and 60% form the cable length from detector B. The first pulses of both measurements are the direct travelled pulses. After the double cable travelling time the reflections could be observed.

It can be concluded, that the double sided PD measurement brings a benefit in higher sensitivity of up to 200% and better localization possibility. The higher sensitivity enables to test longer cables with the same sensitivity compared to single sided measurement. Furthermore the decision between near end and far end PD could be separated easily. In single sided measurements, the difference between near end and far end PD origin is not always clear.

MEASUREMENT ON A HV POWER CABLE

This example show a measurement on a 19.1 km long newly installed 110 kV cable with PD detectors at both ends of the cable, as schematically depicted earlier in Fig. . The PD detector A is on the near end of the cable, together with a DAC system to energize the cable, see Fig. . PD detector B is placed at the far end of the cable.

The PD detectors are synchronized to a time resolution of 10 ns, with an error of another 10ns. This results in an accuracy of about 3 m for locating the PD origin.

During test the operator at the near end of the cable can control the PD detector at the far end, to set its calibration factor and to read out the current PD levels based on IEC60270. Later on, the HF data recorded at the far end unit has been combined with the HF data from the near end unit for locating the PD discharging sites (joint at 13.7 km) , so that the mapping as seen in Fig 14 could be created.

As it can be seen the PD pulses are pinpointed to one joint and the far end termination of phase L1, of which the PDIV was 1.1Uo, The mapping shows PD up to 1.7Uo.

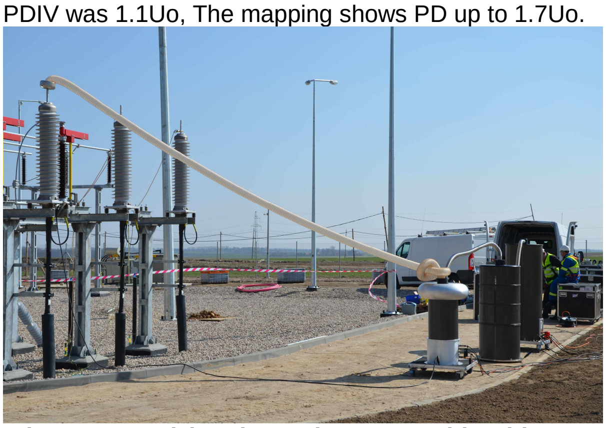

Fig. 13: Energizing the 110kV XLPE cable with a DAC system at the near end.

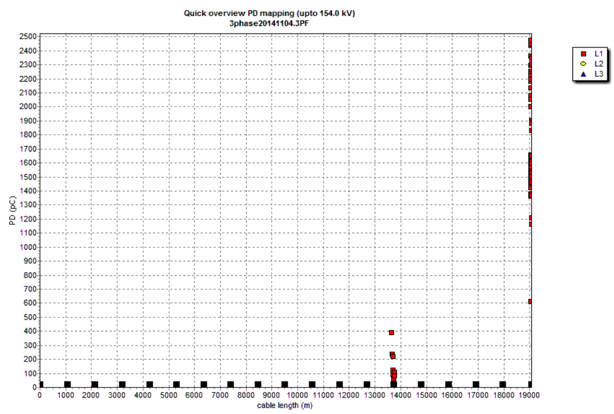

Fig. 14: PD mapping resulting from a double sided measurement on a 19.1 km long cable indicating in Phase L1 PD activity in a joint at 13.7 km position.

CONCLUSIONS

Based on this study the following can be concluded:

1. The presented method of a synchronized PD measurement at both sides of the cable has shown that the sensitivity of on-site PD measurements improves. In particular it provides a more precise PD localization on long cable lengths and therefore a better condition assessment.

2. The single sided measurement in combination with a damped AC power source showed good results in the past years with onsite measurements. To improve the setup a second PD measurement unit was introduced and connected to the other cable end.

3. The double sided measurement is evaluated for improving on the PD localization, especially in relation to longer cable lengths. The attenuation of PD amplitudes was considered as a function of cable length for single and double sided PD detection. Moreover examples for double sided measurements with different cable length were discussed.

4. It can be concluded that based on simulations and measurement the combination of DAC testing with double sided measurement technique, provides an optimal solution for testing very long (E) HV power cables and in providing (up to 30 km) an increased detection and localization ability of PD sources within the cable circuit.

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