SYMMETRIC 3-CHANNEL INDUCTIVE PD DETECTION WITH OPTIMIZED SNR FOR EXTRUDED POWER CABLES

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Abstract: This paper deals with advances in PD detection for power cables resulting in improved SNR for best-possible sensitivity under noisy conditions. It is based on a symmetric 3-channel inductive PD detection (S3CD) requiring to connect the three phases of a cable system in parallel for testing. S3CD is usually performed by inductive coupling at the cable screens (ground). Alternatively, it is possible to apply S3CD to the cable conductors (high voltage potential), to maintain selectivity when testing three-core cables with common screen. Examples from after-installation tests of MV and HV/EHV extrude cable systems will demonstrate the usefulness of S3CD on-site PD measurements.

1 INTRODUCTION

PD measurements on extruded power cables are part of the routine and type test procedures and performed at the cable maker plant. To reach the required sensitivity for PD measurements, low noise high voltage test systems, screened laboratories and line as well as HV filters are required. A coupling capacitor with appropriate capacitance is used for PD detection.

The actual IEC standards for HV and EHV extruded cables require AC after-installation testing [1, 2]. Mobile AC resonant test systems are the well-proven solution for on-site voltage testing of extruded cable systems [3–5].

When performing PD measurements during AC after-installation testing of power cable systems, the actual noise level may hamper sensitive measurement. Furthermore, sensitivity drops with increasing cable length because of PD signal attenuation [6]. When performing PD detection with a coupling capacitor at the cable terminal, the coupling ratio will drop with increasing cable capacitance, proportional to the cable length. The signal-to-noise ratio (SNR) will consequently decrease with increasing cable length. This general effect can be overcome by distributed PD detection directly at the cable accessories and suited PD sensors.

Usually, de-noising of noisy single-end on-site PD measurements is done within the PD measuring system by use of suited filters, gating, pulse-waveform-analysis and other advanced noise-suppression procedures.

This paper deals with advances in PD detection for power cables resulting in improved SNR for best-possible sensitivity under noisy conditions. It is based on a **s**ymmetric **3**-**c**hannel inductive PD **d**etection (S3CD) requiring to connect the three phases of a cable system in parallel for testing. Therefore, the mobile AC test system has to be able to deliver sufficient AC test power for the total capacitance, which in this case, of course, is three times higher compared to single phase testing.

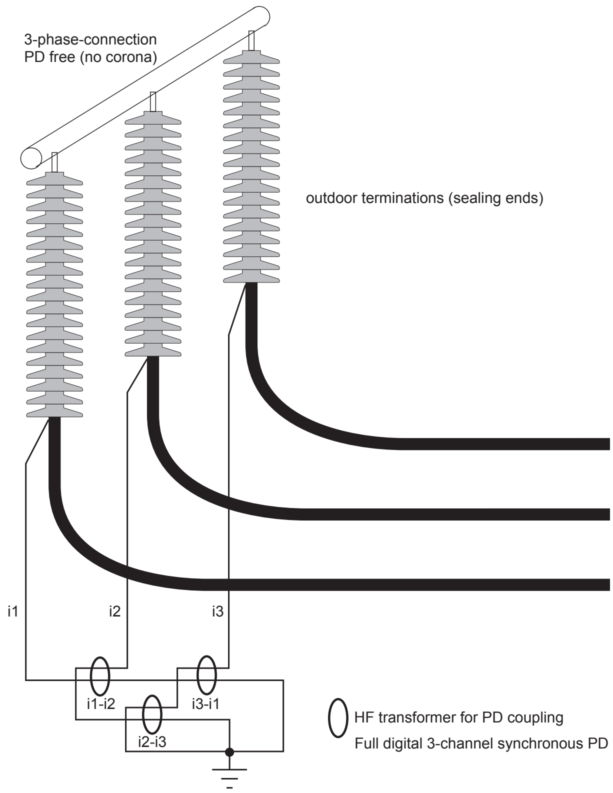

Figure 1: 3-channel differential PD detection

Fig. 1 shows the operating mode of symmetric 3-channel inductive PD detection on ground connections of outdoor cable terminals. In principle, S3CD extends the idea of balanced PD detection (see section 2) from one (bridge) to three differential detectors. Section 3 provides the details on S3CD.

When AC test power demand is no critical issue, S3CD offers several benefits for on-site PD measurements on three-phase extruded cable systems:

- the PD coupling ratio becomes cable length-independent
- common-mode noise is suppressed
- selectivity for each cable is maintained
- the total after-installation test time is reduced (parallel instead of sequential test)

Figure 2: PD-free test set-up for 160 kV resonant test of three phases in parallel

Fig. 2 shows the PD-free connection of three 110 kV outdoor cable terminals for after-installation testing with an AC test voltage of 160 kV using S3CD for low-noise on-site PD measurements.

2 BALANCED PD DETECTION

In low-noise HV labs, straight PD detection with a coupling capacitor in parallel to the test object generally fulfills the relevant standard [7] as well as sensitivity requirements. But with increasing capacitance of the test object signal-to-noise ratio (SNR) becomes worse and may cause demand for improved noise rejection.

Since long, balanced PD detection using bridge circuits is used for noise rejection (see e.g. [8–15]).

Balanced PD detection as shown in fig. 3 is based on the differential measurement in between test object C_X and reference capacitor C_N. Best possible suppression of common-mode interference is reached for symmetry of both arms of the bridge circuit, if C_X and C_N are equal.

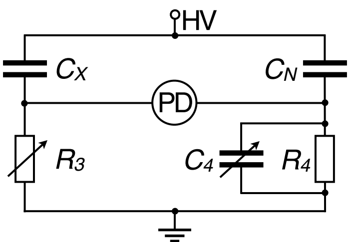

Figure 3: Balanced PD detection based on Schering bridge

In general, C_X and C_N are *not* equal and therefore it makes sense to adjust the bridge for the best common-mode noise suppression. The suppression ratio is obtained by injecting calibration pulses in between HV and ground (corresponding to common-mode noise) and in parallel to C_X (corresponding to PD from the test object).

The circuit in fig. 3 shows a simplified lumped network, only partly representing *real* circuits with distributed parameters. In consequence, common-mode noise suppression will not be ideal in practice. Due to unavoidable differences in both arms of the bridge circuit, the suppression ratio becomes frequency dependent. Narrow bandwidth for PD detection will help to facilitate a high suppression ratio.

3 SYMMETRIC 3-CHANNEL INDUCTIVE PD DETECTION (S3CD)

In contrast to balanced bridge detection, S3CD is actually applied without balancing, using differential detection within each HFCT (HF current transformer) only. Due to the natural similarity of the three phases within one cable system, common-mode noise suppression is fairly good without balancing.

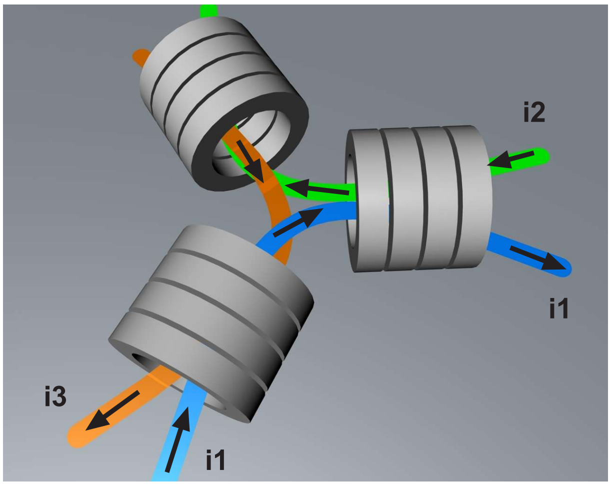

Figure 4: Directed current flow through HFCTs

Fig. 4 illustrates the S3CD symmetry (not showing the HFCT secondary winding). Due to the directed, inverse current flow in each of the three HFCTs, common-mode noise will be subtracted and result in very low differential output. The resulting magnetic field caused by the low-frequent capacitive current is so low, that saturation of HFCT ferrite core cannot occur. The HFCT design can be optimized for PD sensitivity. Depending on the inner diameter of the HFCT and the required conductor cross-section to carry the low-frequent ground current, inductive coupling can be further improved by more turns on the primary HFCT winding (compare fig. 4 and 5). Usually, ground connections are made by insulated wires. Coaxial cables for ground connections would enable capacitive shielding and consequently minimize unwanted coupling of noise.

Table 1 shows the ideal S3CD output. The directed current leads to polarity discrimination depending on the source of pulses (see also blue and red curves in the oscillogram in fig. 6).

		PD source		
		L1	L2	L3
coupling	i1-i2	+q	-q	0
	i3-i1	-q	0	+q
	i2-i3	0	+q	-q

Table 1: S3CD output (ideal)

As already indicated in section 2, the differential output for S3CD will not be zero in practice. The suppression ratio of S3CD is usually in the order of 20 dB, depending on center frequency and bandwidth of the PD detector (see spectra in fig. 6, 7 and 8). This is no disadvantage when S3CD is combined with synchronous three-channel PD detection and 3PARD evaluation [16, 17].

When detecting the three S3CD differential output signals simultaneously, 3PARD evaluation becomes applicable. 3PARD needs pulse magnitudes exceeding the threshold for all three channels. Therefore, the non-perfect suppression of S3CD becomes even essential.

Injecting calibration pulses in each phase L1, L2 and L3 results in the 3PARD shown in fig. 9. According to table 1, the clusters of calibration pulses are in between the axis of the relevant phases. Common-mode noise concentrates in the center of the diagram.

4 S3CD ON HV POTENTIAL

Of course, S3CD application is not restricted to high-voltage cables only. Fig. 5 shows the complete test set-up for after-installation testing of three-core MV cables.

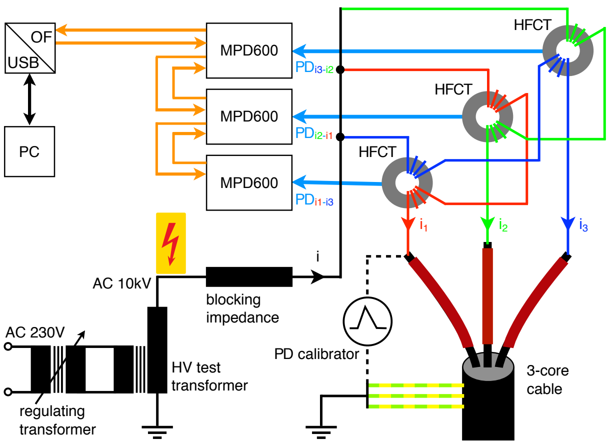

Figure 5: S3CD on three-core cables

In this case, the common ground for all three phases of the three-core cable prevented from S3CD on ground connections. In contrast to the set-up shown in fig. 1, distinguishing PD sources in between the three phases becomes impossible. In consequence, only application of S3CD on high voltage potential (as shown in fig. 5) re-enables proper 3PARD evaluation for three-core cables with common ground.

To perform PD measurements on high voltage potential, potential-free measuring equipment is needed. Battery supply, optical fiber communication and small size of the MPD600 PD measuring units ensures potential-free operation.

Like in fig. 1 and fig. 4, fig. 5 does not show the HFCT secondary winding.

5 RESULTS

The results shown in this section are based on S3CD PD measurements on 6/10 kV XLPE-insulated three-core cables according to the test set-up shown in fig 5.

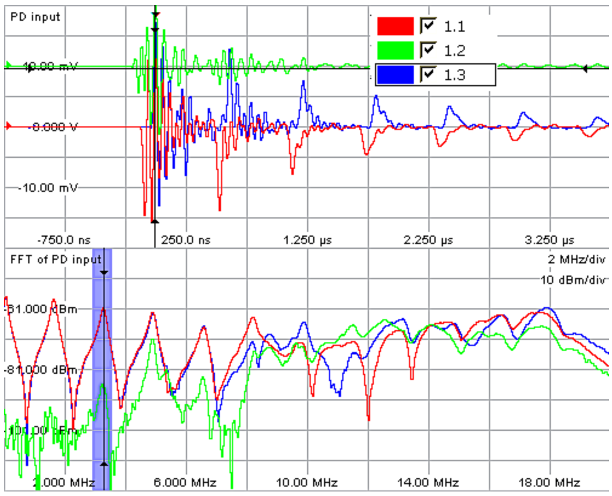

Figure 6: Oscillograms and Spectra of calibration pulses injected in L1

Fig. 6 shows the oscillograms and spectra of calibration pulses injected in phase L1 of a short three-core cable. In accordance with table 1, the S3CD output of HFCT PD_{i1-i3} and PD_{i1-i2} is clearly higher than of HFCT PD_{i2-i3} (the signal polarity is not relevant for 3PARD evaluation). Due to the short length of the power cable, multiple reflection from the open end are present in the oscillograms. Accordingly, the spectra show the typical behavior caused by constructive and destructive signal superimposition. Because of unknown position of eventual PD defects, the pulse spectra have to be carefully checked and the PD instrument settings (center frequency, bandwidth) have to be set for good SNR.

From the spectra shown in fig. 6 it becomes obvious, that all three magnitudes become similar for frequencies > 8 MHz. This is probably due to cross-talk (capacitive coupling) in between the non-screened connections. Coaxial cables would reduce such cross-talk effects.

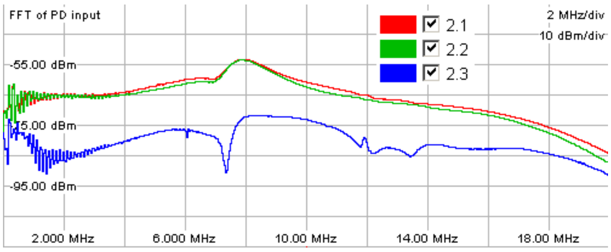

Figure 7: Spectra of cal. pulses injected in L2

Injection of calibration pulses into longer cables results in spectra shown in fig. 7 and fig. 8. The attenuation of propagating pulses through the longer cables leads to lower superimposition effects. The magnitude of the three S3CD outputs is (again) in accordance with table 1, allowing clear discrimination in between the three phases and in between eventually PD and common-mode noise.

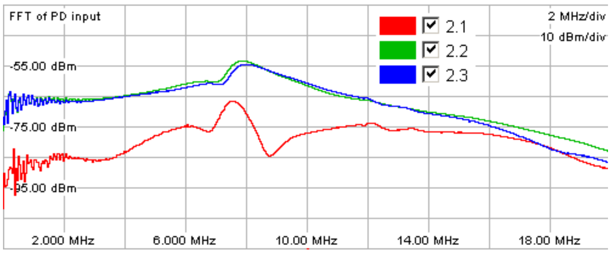

Figure 8: Spectra of cal. pulses injected in L3

3PARD evaluation of calibration pulses injected sequentially in phase L1, L2 and L3 results in the diagram shown in fig. 9.

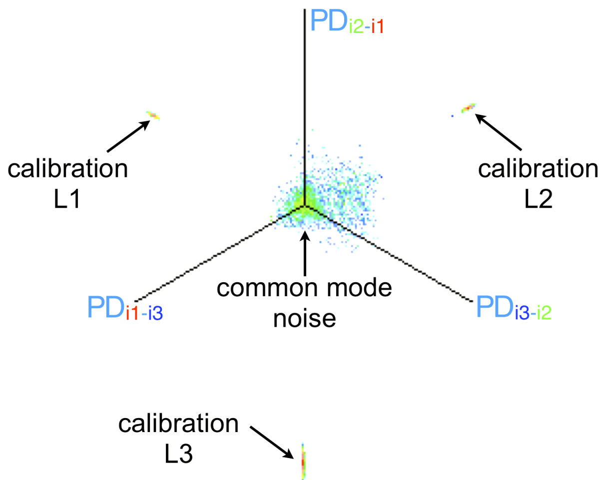

Figure 9: 3PARD of cal. pulses in L1, L2 and L3

The noise level was very low and so the clusters of calibration were focussed in very small spots. The common-mode noise collected in a cluster in the center of the diagram.

During one of the tests on three-core cables, corona discharges occurred at phase L3. Fig. 10 shows the 3PARD and phase-resolved partial discharge (PRPD) pattern only for the marked 3PARD cluster.

The PD threshold was set to 0.5 pC in this test. 3PARD separation led to complete removal of any interferences.

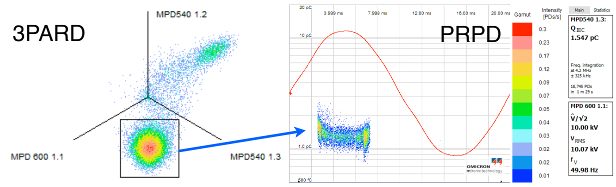

Figure 10: Corona at L3

6 CONCLUSIONS

If limited test power due to capacitive load will not restrict the test procedure to single-phase testing, symmetric 3-channel inductive PD detection (S3CD) will be useful to improve SNR and to speed up testing.

S3CD is possible either on ground connections or on high voltage potential. The latter can be of interest not only for MV three-core cables, because ground connections are exposed to ambient noise, whereas high voltage conductors are screened by the coaxial design of power cables.

For simple reasons, S3CD is not applicable to on-line measurements, especially not to online monitoring in service configuration [18]. For online tests with 24 h / U_0 it would be still possible, if only one phase is used to energize the three-phase cable system.

7 FUTURE PROSPECTS

Fig. 11 shows a PD-free test set-up for S3CD PD measurements on 400 kV outdoor cable terminals at test voltages up to 380 kV.

Figure 11: PD-free test set-up for 380 kV resonant test of three phases in parallel

On-site PD measurements of EHV extruded cable systems are frequently performed with distributed PD sensors built-in or at each cable accessory [6, 19]. But sensitive PD detection at outdoor cable terminals is still an issue. In noisy environment, S3CD helps to perform sensitive PD measurements on EHV cable systems.

The HFCTs used for S3CD were actually not optimized for PD measurements below 1 MHz center frequency. On-site PD measurements show quite often high noise levels at such low frequencies. With S3CD, if necessary combined with optimized HFCTs and balanced detection (bridge circuits) it may become feasible to perform PD measurements at frequencies, where cable damping will not hamper PD detection sensitivity. This may open new strategies for on-site testing on AC submarine cables.

S3CD is not restricted to resonant testing. For example, VLF and OWTS, which are made for high capacitive load, can be used as well as suited after-installation test voltages for S3CD PD measurements.

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