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Partial Discharge Measurement and Monitoring on High Voltage XLPE Cables

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SUMMARY

To check production quality, partial discharge (PD) measurements are performed on underground cables or cable drums. PD impulses propagate through the cable and are reflected at the ends and on joints. By measuring the delay between the impulse which is directly coming into the PD instrument and the impulse which is reflected at the end, a location of the PD source can be done. Due to reflections, partial discharges generally occur as pulse groups, which can lead to superimposed oscillations of the PD filter which is required to determine the charge value as per IEC 60270. With a new approach of simultaneous measurement at different receiver frequencies the superposition effects can be eliminated.

With PD monitoring the reliability and availability of the equipment will increase and the life time of the cable lines will be extended. Other important benefits of monitoring are higher safety for the personnel and reduced environmental risks.

In the paper recommendations are given for the application of monitoring techniques to HV XLPE cable systems. Particular attention is paid to: Sensitivity of PD measurements, multi-channel evaluation technique for separation of PD sources and suppression of external noise, selective parts of the hardware of the monitoring system like e.g.: inductive PD sensor, PD acquisition unit, optical communication technology, power supply solutions and system engineering requirements;

KEYWORDS

Multi-channel PD systems, simultaneous PD measurement at all joints, digital PD instruments, PD measurement on long underground cables, damping of impulses along the cable

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INTRODUCTION

The long term reliability of an underground cable installation depends on many factors: good materials, good design and manufacturing, successful approval testing, defined operating conditions and perfect assembly of accessories on site. It is considered necessary to carry out field testing to confirm the quality of the proper installation. The purpose of after-laying testing is to check that the cable laying and accessory installation have been correctly executed. Testing is required to confirm contractual conditions and enable the owner-ship of the system to be transferred from the contractor to the customer. It is not the purpose of the after-laying testing to demonstrate that the manufactured quality of the cable or accessories is good. In the high voltage field, mounting of joints and terminations should be done by well trained and skilled fitters following well proven erection procedures. Efficient quality assurance (QA) procedures should always be the basis for the formal take over by the customer of installed HV cable systems. [1].

AFTER-LAYING TESTS ON HIGH VOLTAGE CABLES

The following two IEC standards contain after-laying tests on HV cables:

- IEC 60840, Edition 3.0 "Power cables with extruded insulation and their accessories for rated voltages above 30 kV up to 150 kV – Test methods and requirements [2]

- IEC 62067, Edition 1.1 "Power cables with extruded insulation and their accessories for rated voltages above 150 kV up to 500 kV – Test methods and requirements [3]

The tables 1 and 2 show the test voltages after-laying.

1	2	3	4 [1)]	5 [1)]	6 [1)]	7 [1)]	8 [1)]	9
Rated voltage	**Highest voltage for equipment**	**Value of U_0 for determination of test voltages**	**Voltage test of 9.3 and 12.3.7**	**Partial discharge test of 9.2 and 12.3.4**	**Tan δ measurement of 12.3.5**	**Heating cycle voltage test of 12.3.6**	**Lightning impulse voltage test of 12.3.7**	**Voltage test after installation of 15.2**
U	U_m	U_0	2,5 U_0	1,5 U_0	U_0	2 U_0		
kV	kV	kV	kV	kV	kV	kV	kV	kV
45 to 47	52	26	65	39	26	52	250	52
60 to 69	72,5	36	90	54	36	72	325	72
110 to 115	123	64	160	96	64	128	550	128
132 to 138	145	76	190	114	76	152	650	132
150 to 161	170	87	218	131	87	174	750	150
[1)] If necessary, these test voltages shall be adjusted as stated in 12.3.1.								

Table 1 *Test voltages according IEC 60840*

Rated voltage		**Test voltage (phase-to-ground)**
U	***U_0***	
kV	kV	kV r.m.s.
220 to 230	127	180
275 to 287	160	210
330 to 345	190	250
380 to 500	220	260
500	290	320

Table 2 *After-laying test voltages according to IEC 62067*

HIGH VOLTAGE TEST SOURCES

In order to reduce the dimensions of AC test equipment, different types of resonant test sets have been developed

- Resonant test set with variable inductance (mainly used in laboratories)
- Resonant test set with variable frequency normally in the range of 20 to 300 Hz

The last type is lighter than traditional transformers or resonant test sets and can be transported to the field on normal trucks. Figure 1 shows an AC resonance test system with variable frequency, figure 2 shows the corresponding block diagram.

Fig. 1 *Resonance system for after-laying tests on cables*

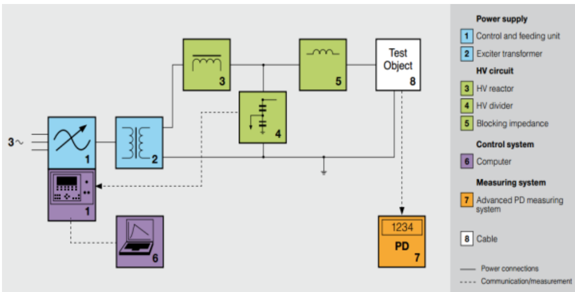


Fig. 2 *Block diagram of AC resonant test system for cable testing*

PARTIAL DISCHARGE MEASUREMENT

The purpose of after-laying PD testing is to check that the cable laying and accessory installation have been correctly executed. In the standard IEC 60270 the procedure of PD testing is described. The test circuit is shown in figure 3. The capacitance C_a represents the cable, the capacitance C_k the coupling capacitor, CD is the measurement impedance (Quadripole) and MI the PD measurement instrument.

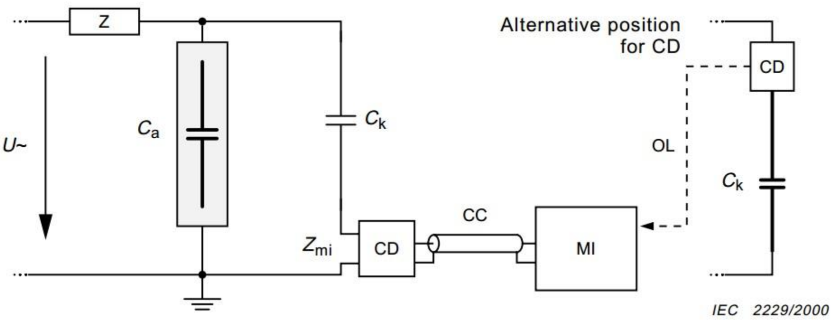


Fig. 3 *Test circuit for partial discharge measurement according to IEC 60270*

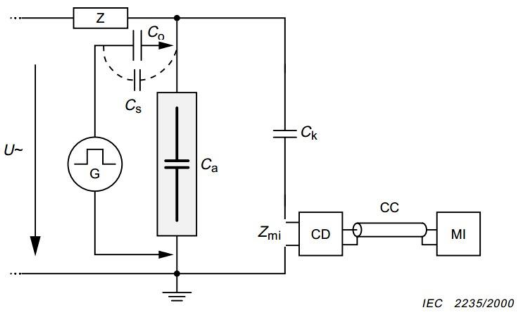


Fig. 4 Calibration according to IEC 60270 (general)

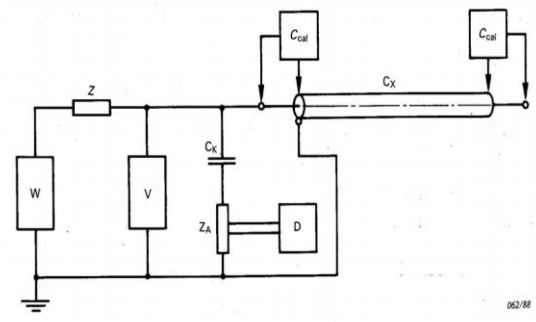
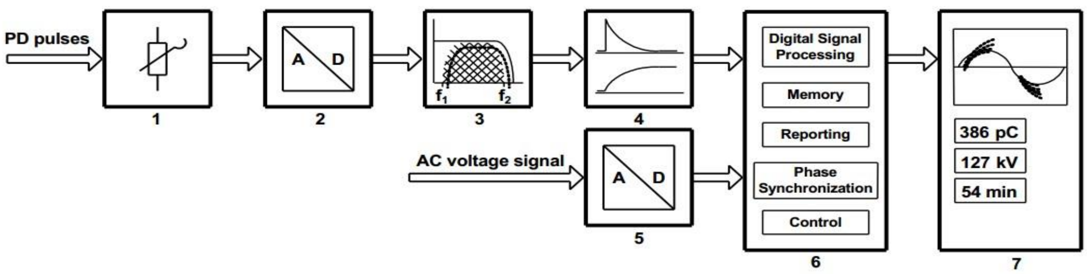


Fig. 5 Calibration according to IEC 60885 (cables)

The general calibration of the PD measurement circuit according to IEC 60270 is shown in figure 4. The calibration for PD measurements on cables according to IEC 60885-3 is shown in figure 5 [4]. Modern PD instruments are working digitally. This has important advantages especially for long underground cables. With a communication over fibre optical cables, several instruments can measure synchronously within a few nanoseconds. This way PD instruments can be positioned on each joint along the cable to detect PD from the joints and the end terminations with high sensitivity. Figure 6 shows the block diagram of such a digital PD instrument.



a) Direct A/D conversion of the input PD pulses

1 – Attenuator
2 – A/D converter for PD pulses
3 – Digital band-pass filter
4 – Numerical integrator
5 – A/D converter for AC voltage
6 – Acquisition unit
7 – Evaluation and visualization unit

Fig. 6 Block diagram of a digital PD instrument (IEC 60270 draft)

Figure 7 shows a high voltage underground cable with joints and corresponding link boxes for cross-bonding of the cable shield and for grounding. One end of the cable is terminated with an outdoor termination the other end is connected to a GIS. An optical fibre cable is installed together with the HV cable for communication of the PD instruments to get them synchronised. Each PD instrument acts as repeater for the optical signals. This way the length of the fibre optical cables is not critical because the digital signals along the optical cable are repeated with each instrument. All PD instruments can be mounted into the link boxes and can stay there for the high voltage tests of all phases. The simultaneous access of all PD instruments is done normally from the end of the cable where the high voltage test set is located. So the whole test procedure can be done from one place.

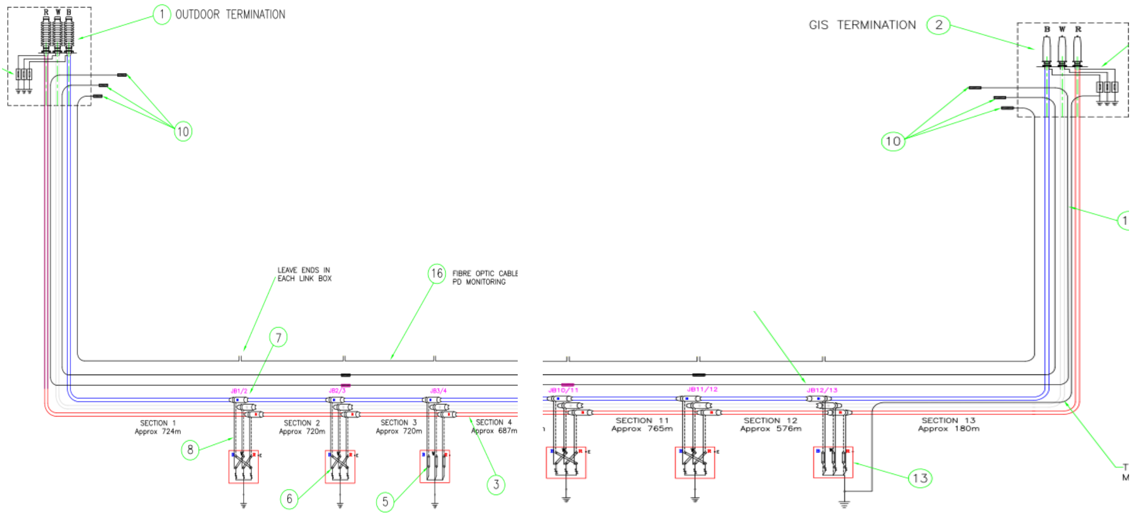


Fig. 7 *Typical cable scheme with link boxes for cross-bonding (6)and earthing (5 and 13)*

If partial discharges are generated in the cable, in the joint or in the terminations they are passing through the shield of the cable. They can be picked up in the link boxes by using special high frequency current transformers (HFCT's, figures 8 and 9). With the split core the HFCT can be mounted around the jumper in the link box.

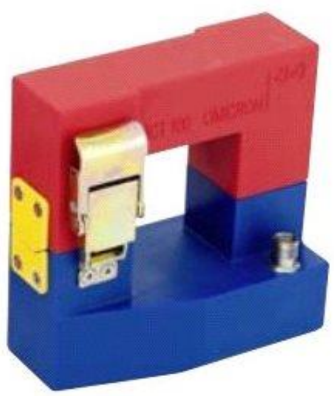


Fig. 8 *High frequency current transformer (HFCT) with split core*

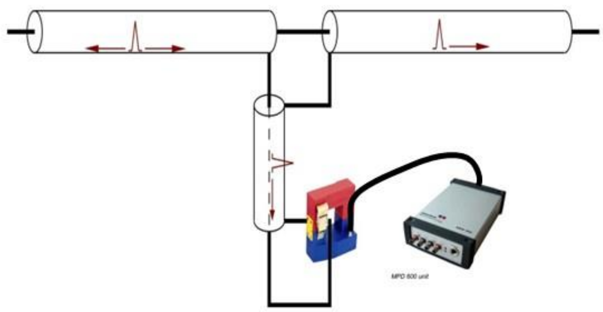


Fig. 9 *Measurement principle with HFCT in the link box*

The whole test arrangement can be seen in figure 10. Three units of MPD600 are used in connection to HTCT's on both cable terminations and on each joint respectively the link box. Additionally one MPD600 is connected to a coupling capacitor at the cable outdoor termination by means of a Quadripole, which enables also the voltage measurement. With this MPD600 channel all other channels can be synchronised. This is very important because otherwise there is no information of the phase angle of the PD's referred to the test voltage, which is necessary for the interpretation of PD patterns.

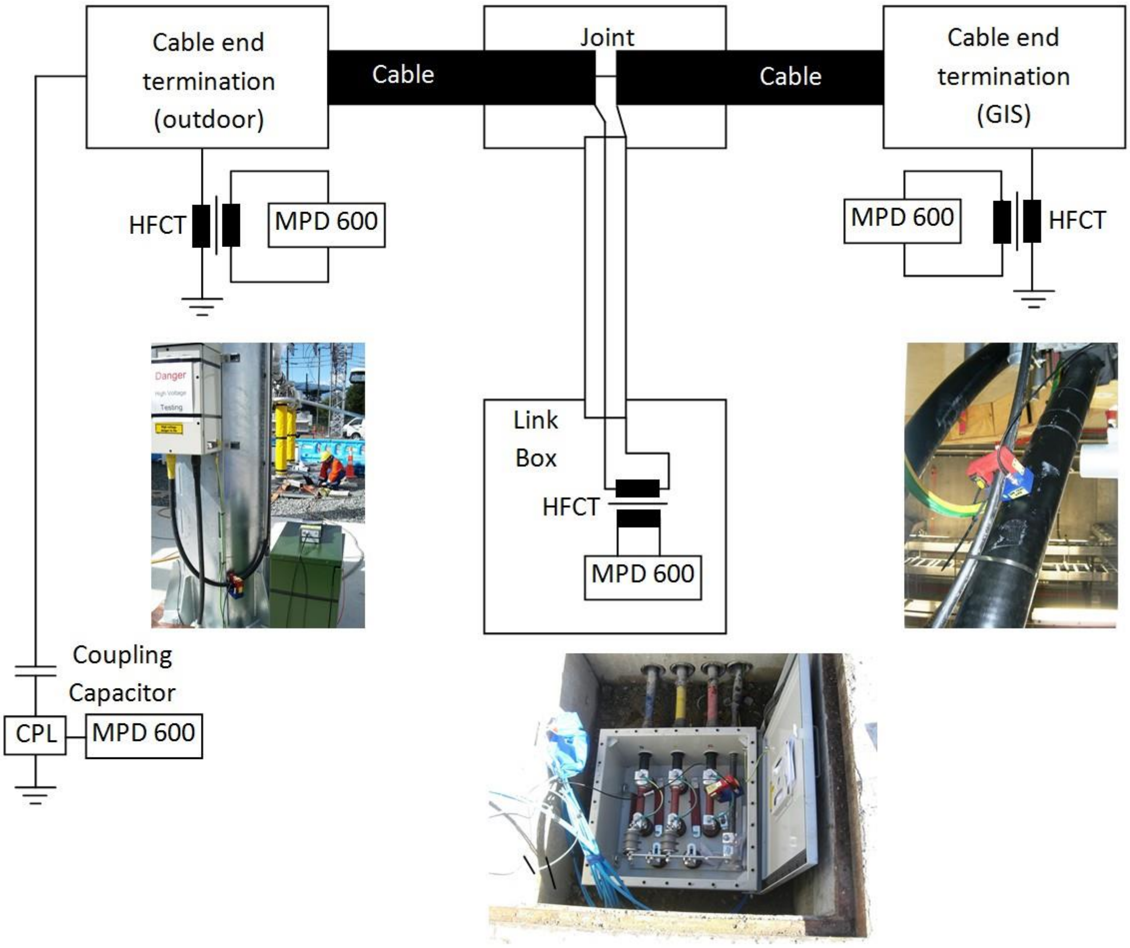


Fig. 10 *Test arrangement with MPD600 units at the coupling capacitor, the terminations and the joints*

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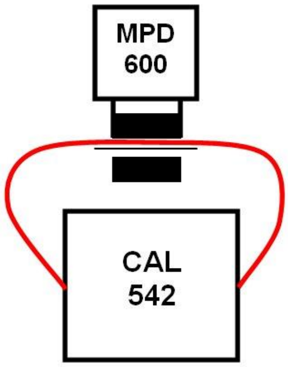

Fig. 11 *Performance check of HFCT's (principle)*

Fig. 12 *Performance check of a HFCT in a link box*

The MPD600 which is connected to the coupling capacitor can be calibrated according to the standards IEC 60270 and 60885 (figures 4 and 5). The standards don't include the calibration of PD instruments which are connected to HFCT's. A real calibration is not possible because no impulse can be injected directly into the closed and buried joint. Therefore a check of performance is normally done (figures 11 and 12). The calibrator is connected to one turn of wire through the core of the HFCT. The check shown in figure 12 includes also the mutual coupling of the jumper and the cable between the joint and the link box. Normally the PD correction factor is approximately 5.5 for one turn through the core window. The correction factor is nearly constant for PD measurement frequencies from 500kHz up to 6MHz.

Selection of the PD Measurement Frequency

In IEC 60270 lower and upper frequency limit are given for wide band PD instruments.

In combination with the coupling device, this type of instrument constitutes a wide-band PD measuring system which is characterized by a **transfer impedance** $Z(f)$ having fixed values of the **lower and upper limit frequencies f_1 and f_2**, and adequate attenuation below f_1 and above f_2. Recommended values for f_1, f_2 and Δf are

$$30\ \text{kHz} \le f_1 \le 100\ \text{kHz};$$

$$f_2 \le 500\ \text{kHz};$$

$$100\ \text{kHz} \le \Delta f \le 400\ \text{kHz}.$$

Spectrum of the Interference

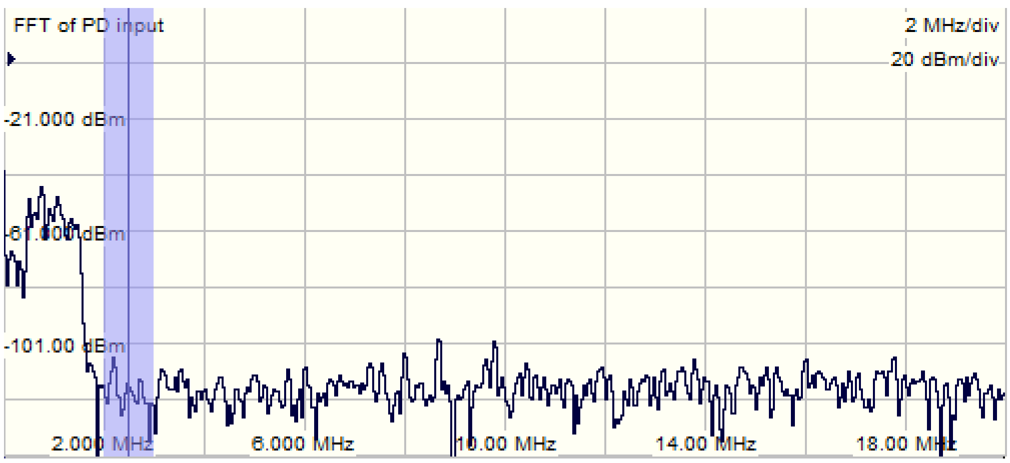

Fig. 13 *Spectrum of external interference at a joint*

A typical case is shown in figure 13. It can be seen that the external interference noise is quite high for measurement frequencies below 2MHz. The bar shows the chosen frequency settings. The lower frequency is 2MHz the upper frequency is 3MHz. This is not fulfilling the IEC 60270 standard, which was written mainly for PD measurements in a laboratory, but a good compromise for on-site testing.

Damping of PD Impulses along the Cable

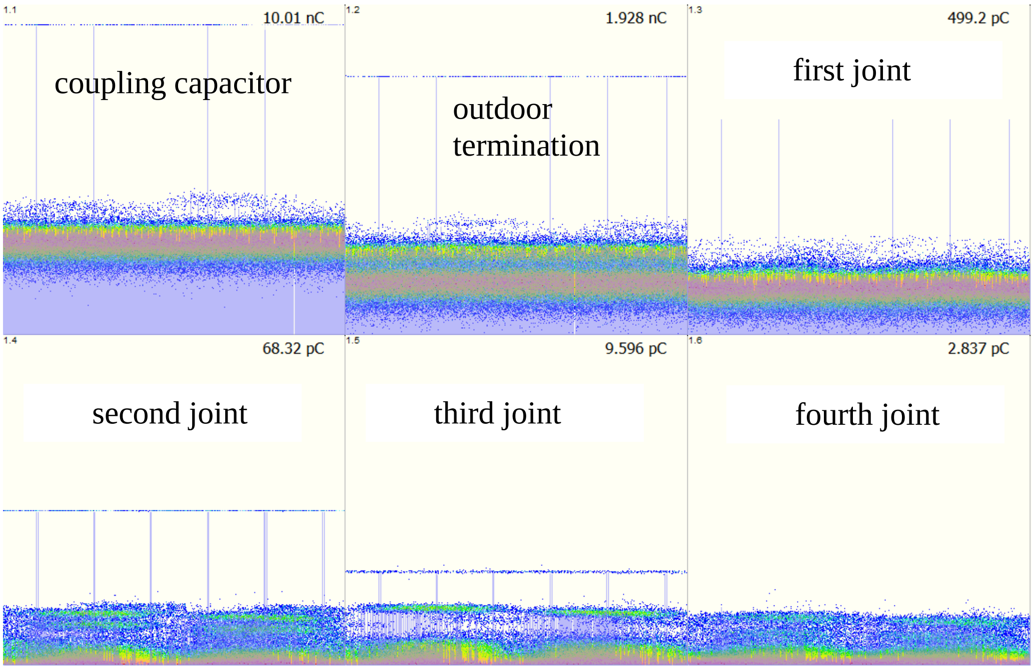

***Fig. 14** 10nC at the coupling capacitor yellow phase*
1.1 = coupling capacitor, 1.3 = joint 1-2, 1.4 = joint 2-3, 1.5 = joint 3-4

Figure 14 shows the damping of a calibration impulse of 10nC, which is injected into the termination of a 220kV cable. The measurement frequency range is 2MHz to 3MHz. The 10nC calibration impulse can be seen up to the third joint. But small partial discharges can be seen at the joint of origin only. But this is no disadvantage, because PD's are expected at the joints and terminations mainly. So a location of the PD fault is much easier.

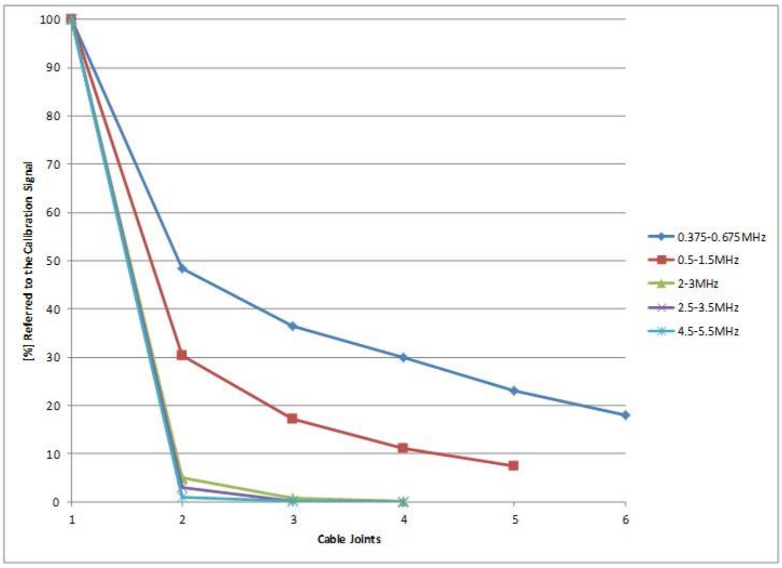

***Fig. 15** Damping of PD impulses along a cable for different measurement frequencies*

In figure 15 the damping for HF impulses on a 220kV cable is shown for centre frequencies from 500kHz up to 5MHz. This cable shows a massive damping for high frequencies. This behaviour was reported by different authors especially for high voltage cables. The reason for this high damping is the high influence of the semiconductive layers around the inner conductor and at the outer surface of the main insulation.

CASE STUDY – PD TESTS ON A NEW 220kV CABLE

A 220kV cable with a total length of 8,4 km was commissioned and a partial discharge measurement was done with a test voltage of 180 kV for one hour for each phase. Figure 16 shows the preparation of the MPD600 with the batteries and the HFCT's, figure 17 the resonance test set with the voltage divider, the blocking impedance and the coupling capacitor. All HFCT's were equipped with an air gap of 2 x 0,2mm in the Ferrite core to prevent core saturation. The PD correction factor was found to be k = 5,6 for each HFCT.

Fig. 16 *Preparation of the MPD600 with batteries and HFCT's. The HFCT's were equipped with an air gap in the core to prevent core saturation*

Fig. 17 *HV resonance test set with voltage divider, blocking impedance and coupling capacitor for PD measurement*

HFCT's were connected to the terminations of the cable at the outdoor (figures 18 and 19) and the GIS side (figure 20).

Fig. 18 *Outdoor termination with the HV test setup*

Fig. 19 *HFCT at the outdoor termination*

All link boxes were equipped with MPD600 PD instruments. This could be done for a part of the 12 link boxes without any restriction. But others could be accessed only during the night to keep the disturbance for the public traffic as low as possible. The distance between each two link boxes was approximately 700 meters. The used system was really helpful to minimise the access to the link boxes as much as possible.

Fig. 20 *HFCT at the GIS termination*

Fig. 21 *Opening of the lids of a link box*

Figure 21 shows the lifting of a cover of a link box with a small excavator. Figure 22 shows a link box close to the highway, figure 23 in the bus lane of a highway.

Fig. 22 *Link box close to the highway*

Fig. 23 *Link box on the highway*

In total 16 MPD600 units were used. After the installation of all MPD600, they were checked from the near substation, where the voltage source was located. The MPD600 at the coupling capacitor was calibrated. The correction factor was approximately k = 1,3. This quite small correction factor was achieved by the relatively high coupling capacitance of more than 8nF. The voltage correction factor could be determined when the cable was energised by the resonance test set with a voltage of 60kV. Figure 24 shows a link box for cable grounding with installed HFCT and MPD600 (in the blue bag). The Diesel aggregate, which supplied electrical power to the resonance test set is visible in figure 25, the scheme, the test voltage profile and the operation screen is shown in figures 26 and 27. The final test voltage was 180kV, the test frequency was 25.95Hz, the test current was 68.1A. The measurement frequency for all MPD600 units was set to a range from 2Mhz to 3MHz. A lower frequency was not possible due to the interference.

Fig. 24 *Link box for cable grounding with installed HFCT and MPD600 (in the blue bag)*

Fig. 25 *Diesel aggregate as source for the resonance test set*

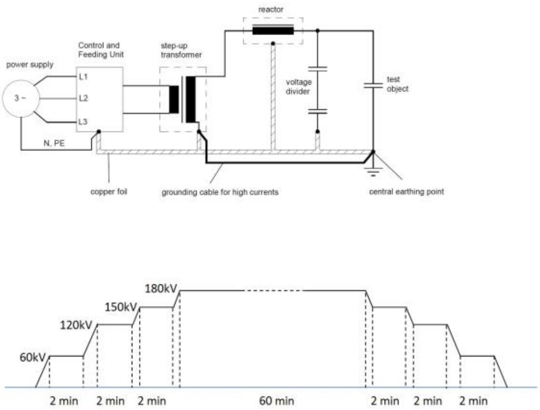

Fig. 26 *Scheme of the resonance test set and profile of the test voltage levels*

Fig. 27 *Screen of the operation unit of the resonance test set.*

Gating

The resonance test set uses IGBT's as switching semiconductors. They produce strong impulses, which cause high interference impulses on the MPD600 instruments, especially to those units which are rather close to the resonance test set. The MPD600 unit 2.1 was installed with an antenna close to the IGBT circuit to receive the switching impulses. The unit 2.1 was used as gating unit. During the time of the switching impulses the signals of all other units are blocked by the MPD600 software. Due to the fact that this is done by software, this gating can be deactivated also for the replay of all recorded streams later on. The dead-time of the gating was chosen to +/-50us, the trigger level was set to 500pC. That means that all impulses at the unit 2.1. with more than 500pC will block the PD acquisition of all other units for a time of +/-50us. According to IEC 60270 it is allowed to block measured signals by hardware gating up to 10% of the cycle, if the impulses are synchronous to the test voltage.

IEC 60270: *"For this reason, the signal should not be blocked by the gate for more than 2 % of each test voltage period in alternating voltage systems". – "If, however, several mains-synchronized interference sources per period are present, the blocking interval limit may be increased to 10 % of the test voltage period.*

This condition was fulfilled during all tests.

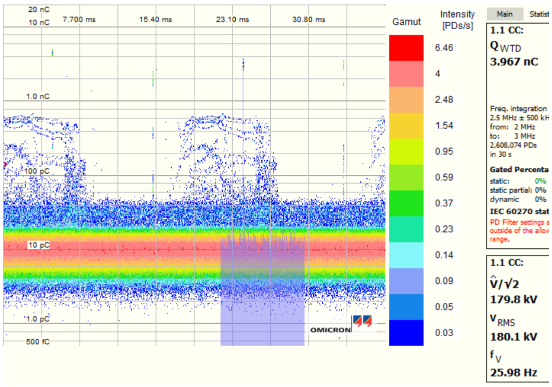

Fig. 28 PD measurement at the coupling capacitor without gating

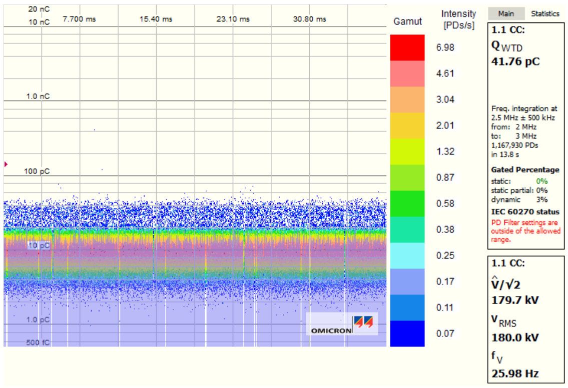

Fig. 29 PD measurement at the coupling capacitor with gating

Figures 28 and 29 show the PD results at the coupling capacitor without and with gating.

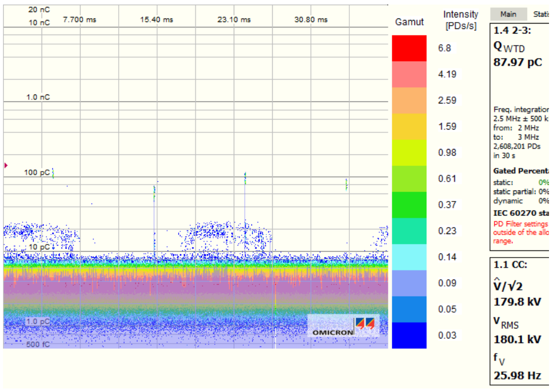

Fig. 30 PD measurement at joint two without gating

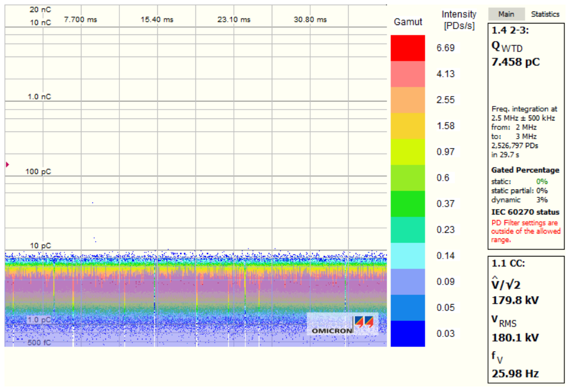

Fig. 31 PD measurement at joint two with gating

Figures 30 and 31 show the PD results at 180kV at joint two respectively at joint 2-3 without and with gating.

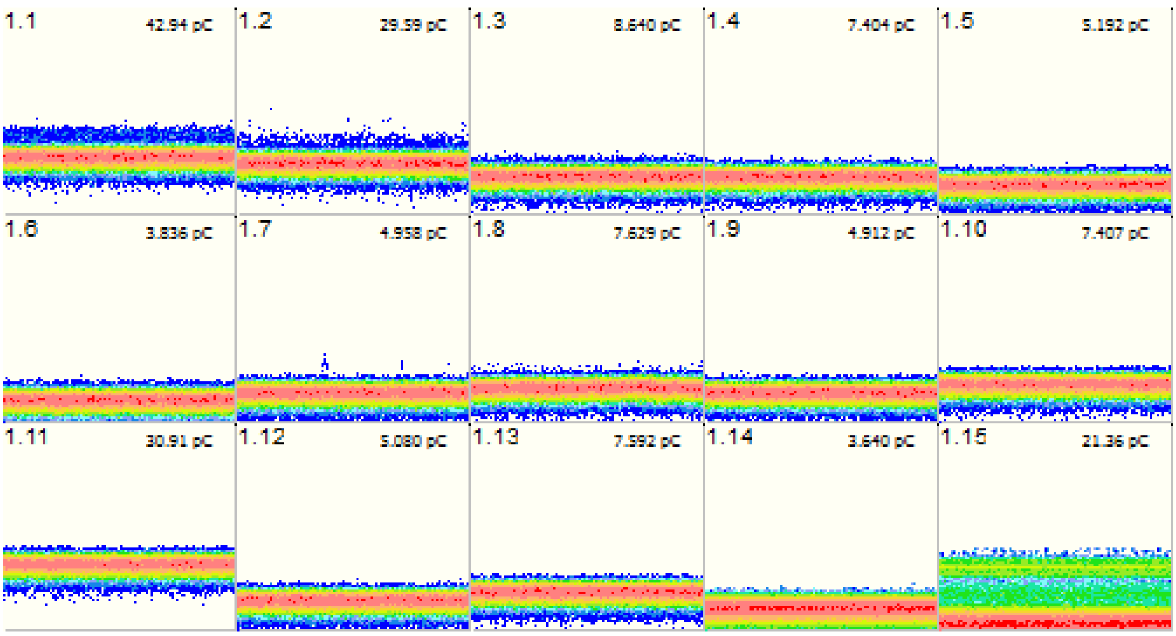

Fig.32 *PD measurement at 180kV with 15 MPD units - 1.1=coupling capacitor, 1.3=joint 1-2, 1.4=joint 2-3, 1.5=joint 3-4, 1.6=joint 4-5, 1.7= joint 5-6, 1.8= joint 6-7, 1.9=joint 7-8, 1.10=joint 8-9, 1.11=joint 9-10, 1.12=joint 10-11, 1.13=joint 11-12, 1.14=joint 12-13, 1.15=end terminal GIS*

The PD results at 180kV of all MPD600 units are shown in figure 32. The tests could be successfully finished within 3 ½ days including the safety instructions, mounting of MPD600 to all link boxes and changing the jumpers to all phases. All tests were going well. No partial discharges could be detected above the noise level.

PD MONITORING ON HV CABLES

The concept of applied continuous monitoring system is presented in Fig. 1. The signals from different sensors measuring partial discharges, distributed temperature, oil pressure in terminations and sheath voltage limiters are acquired by multi-channel data acquisition units.

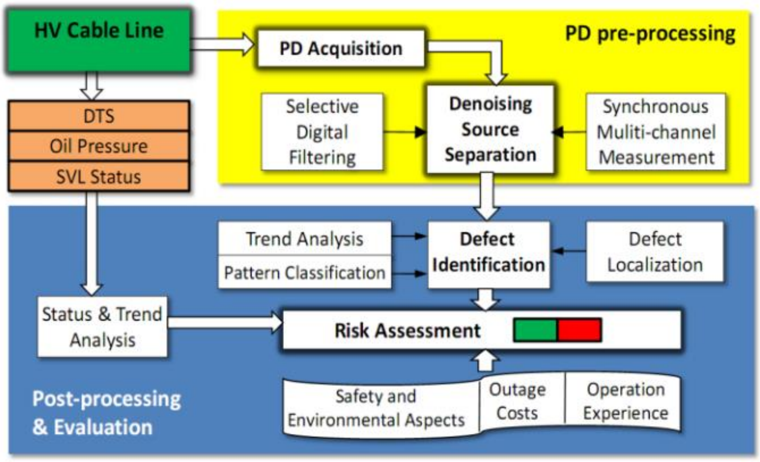

Fig.33 *Concept of a cable PD monitoring system*

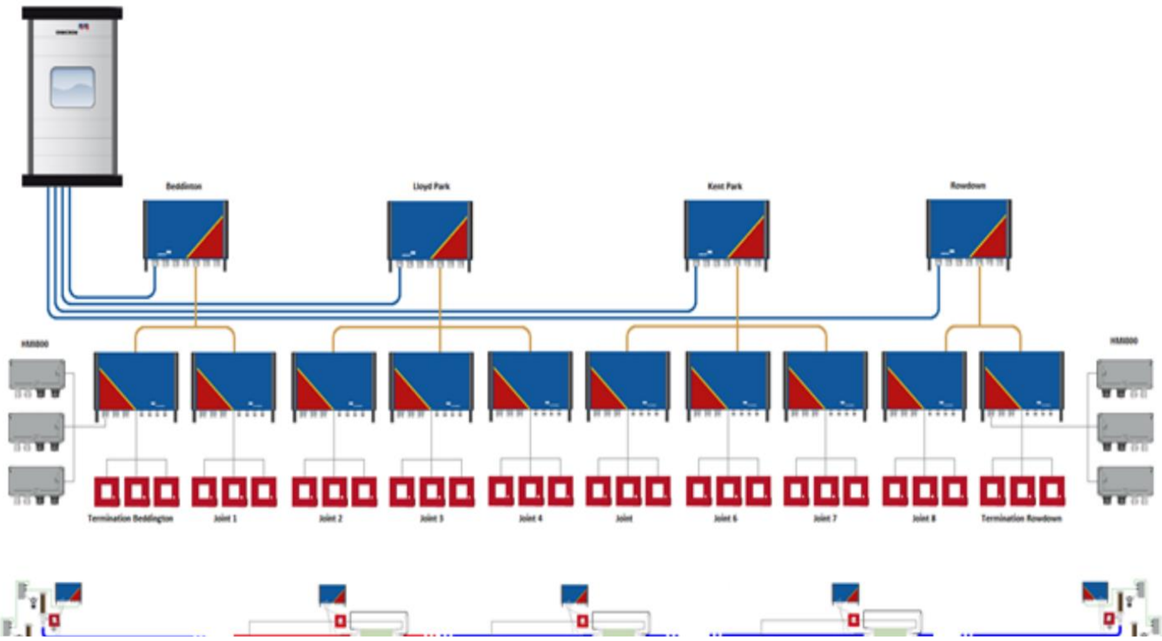

Fig.34 *Schematic diagram of a monitoring system*

The distributes sensor system at each joint is similar to the described on-site PD measurement system. In case of PD signals, the acquisition unit performs advanced pre-processing of the raw data. The disturbances are removed and main characteristics of the PD signal are determined. The output of the data pre-processing is transferred to a server that enables long-term data storage. Advanced intelligent pre-processing reduces the amount of data to adequate levels for transmission over a communication network [5].

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