Technical Report
ICM*flex*

OFF-LINE PD AND TAN DELTA TESTING ON MV/HV CABLES USING THE ICM*flex*

Partial discharge and tan delta measurements on MV/HV cables with Power Diagnostix's ICM*flex* can reduce maintenance costs and improve reliability of the distribution class cables.

Service aged distribution class cables affect the reliability of the distribution network. For this reason, factory acceptance testing as well as field testing is required to assess the severity of the degradation process.

Partial discharge (PD) activity is an important indicator to evaluate the level of degradation of the insulation of high voltage (HV) equipment in general. The mapping of the partial discharge activity versus the length of the cable allows identifying the discharges within the cables and the accessories. Regarding the high voltage excitation of the cables under test, there are different methods available. The fixed frequency resonant test set running at 50/60 Hz power frequency offers an excellent match of the service condition; however these test sets are relatively heavy and costly. More cost-effective solutions would be variable frequency resonant test sets, damped oscillating wave, or very low frequency (VLF) excitation.

Partial discharges

In order to insulate power cables, solid and liquid insulation materials are used that are able to tolerate an electrical field, which exceeds by far the normal operational field strength. Imperfections within the cable can occur during production process and may remain undetected during first testing or can also develop during service. Partial discharges are enabled when an imperfection, having a lower inception field, exists, such as voids (gas inclusions).

Figure 1 shows the phase-resolved partial discharge (PRPD) pattern of void discharge with a low availability of starting electrons.

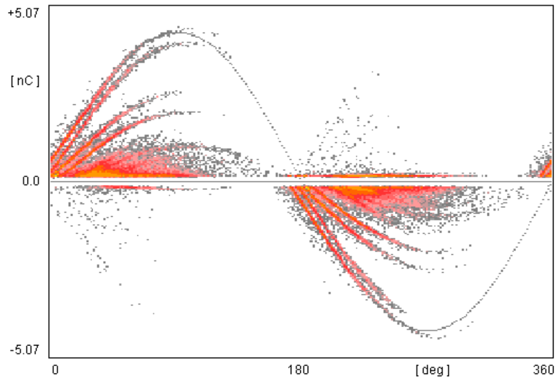


Figure 1: PRPD pattern of void discharge

Also, imperfections, such as sharp metallic inclusions, strongly increase the local electrical field within the insulation. In a gaseous insulation, occurrence of partial discharge requires that the critical field strength is exceeded and that there is a free ionised electron, which can be accelerated in this electric field. Then the initial accelerated electron causes an electron avalanche. The statistical properties of these processes determine the partial discharge pattern, and that is very important concerning identification and interpretation of the discharge activity. In this context, Figure 2 demonstrates the PRPD pattern of internal discharges in a prefabricated EPR cable joint, which then can be useful for later pattern analysis.

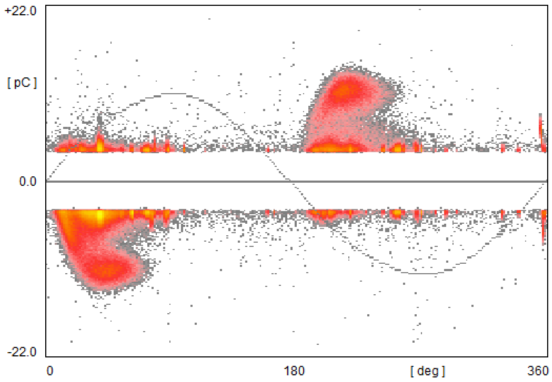


Figure 2: PRPD pattern of internal discharges in a prefabricated EPR cable joint

The ICM*flex* measurement system for partial discharge, tan delta, power factor, capacitance, and power frequency

The ICM*flex* high voltage family offers inherent operator safety and greatly simplifies distribution class cable testing as well as rotating machine, stator bar testing, and other field tasks involving PD detection, tan delta measurements, and PD fault location.

The ICM*flex* is designed to simplify the application and to combine different measurement tasks in one instrument. Its principle of operation minimises testing and operation time.

Figure 3 shows the 50 kV version of the ICM*flex* together with an HV filter.

Figure 3: The ICMflex and HV filter (50 kV version)

Typical end users are:

- Service groups testing motors, generators, and accessories
- Service groups testing high voltage cables, terminations, and joints
- Factories and manufacturers of cables and generators
- Maintenance and repair shops
- High voltage laboratories
- Research and development departments in industry, e.g., special designs for university projects

With the unique concept of the ICM*flex,* the entire acquisition hardware is placed on HV potential, right at the position where the signals are, hence, no signal cables are required. The ICM*flex* is fully computer-controlled, and the communication is provided via Bluetooth or fibre optic serial link. The instrument operates with any fixed or portable HV power supply, like transformers, hipots, resonant test systems as well as modular components.

Calibration procedure

In order to be able to perform PD measurements and PD fault location on cables, the calibration of the apparent charge and the cable length are required. Since the test specimen has a capacitance against the ground shield (for MV/HV cables varying from 200 pF/m to 425 pF/m), the cable capacitance causes strong attenuation of the injected pulse. The difference between the injected and measured charge level is the k factor, the overall attenuation factor of the measurement circuit. The k factor must be compensated by the calibration. Figure 4 illustrates a general MV cable measurement setup.

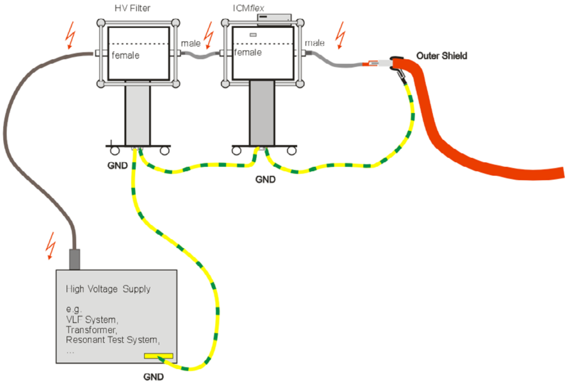


Figure 4: MV cable measurement setup

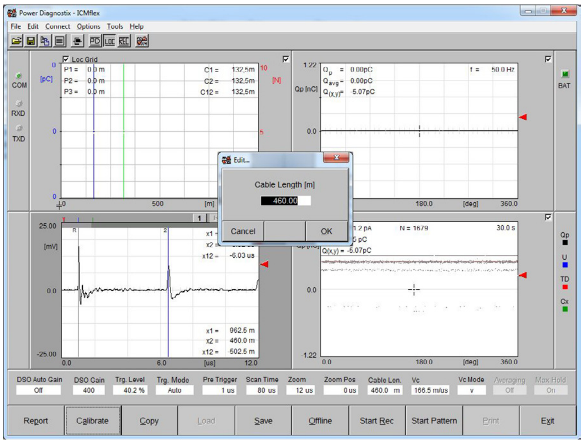
For the laboratory acceptance tests, common calibration levels are in the range of 2 pC to 10 pC. Nevertheless, for on-site measurements, the set-up sensitivity usually does not allow such a sensitive calibration. For this reason, calibrations are done with injection levels from 100 pC to 2 nC in accordance with the IEC 60270 (below 1 MHz). Figure 5 shows a calibrator CAL1B connected to an MV cable (on-site).

Figure 5: CAL1B connected to an MV cable (on-site)

Furthermore, after IEC 60270 compliant calibration of the apparent charge, the cable length or pulse velocity must be determined to be able to perform PD fault location using the time domain reflectometry (TDR) principle. One of the two values must be known prior to tests. Some typical values for the velocity of propagation in relation to the cable insulation tape are shown in the table below. Please also note that these values can vary, depending on the nominal voltage and dielectric strength.

Insulation Type	Vc (m/μs)	Vc /2 (m/μs)
XLPE	148-168	73-84
PILC	147	73
EPR	165	82
Vacuum	300	150

The charge injection principle is the same as with the calibration of the apparent charge. To see the necessary reflections for the TDR, higher charge levels can be required. For calibration of the cable length, the cable terminations must be disconnected on both sides for a full reflection of the wave signal at infinite impedance. Figure 6 shows the calibration of the cable length with the ICM*flex* software.



P1 = 0.0 m
P2 = 0.0 m
P3 = 0.0 m
C1 = 132,5m
C2 = 132,5m
C12 = 132,5m
Q_p = 0.00pC
Q_{avg} = 0.00pC
$Q_{(x,y)}$ = 5.07pC
f = 50.0 Hz
Cable Length [m] 460.00
x12 = -6.03 us
x1 = 962.5 m
x2 = 460.0 m
x12 = 502.5 m
N = 1679
30.0 s
Q(x,y) = -5.07pC
DSO Auto Gain Off
DSO Gain 400
Trg. Level 40.2 %
Trg. Mode Auto
Pre Trigger 1 us
Scan Time 80 us
Zoom 12 us
Zoom Pos 0 us
Cable Len. 460.0 m
Vc 166.5 m/us
Vc Mode v
Averaging Off
Max Hold On

Figure 6: Calibration of the cable length with the ICMflex

Standard PD measurement

For a standard PD measurement, a successful calibration procedure is required as described. Before switching on the voltage to carry out the PD tests, the background noise level must be observed. The correct device setting must be applied to prevent occupying the A/D converter with converting background disturbance pulses. In case additional noise cancellation is required, the ICM*flex* also offers a gating option: Either analogue gating or gating via a fibre optic gating transmitter. These two gating methods apply to disturbances caused by the power supply and by external sources.

After the voltage has been switched on, the next step is finding the PD inception voltage (PDIV) level. For example, according to IEEE 400-3, a healthy cable doesn not show a sign of PD activity before reaching a voltage level lower than $2U_n$. Once the PDIV is reached, the PD pattern can be mapped and compared with typical PRPD pattern from known PD origins. There are also related discharge levels, such as Q_p and Q_{IEC} and the average discharge current (NQS),which are displayed in the ICM*flex* software. Figure 7 shows the PD pattern of a surface discharge.

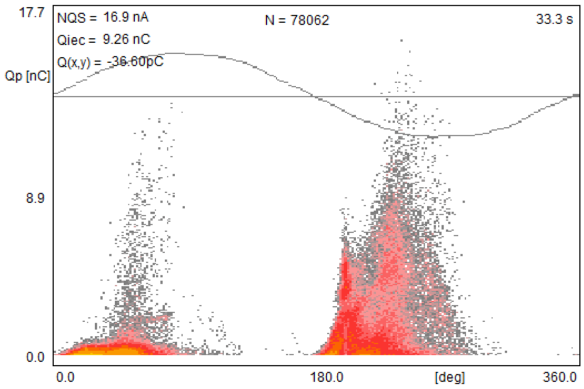


Figure 7: Surface discharge (PD pattern)

Furthermore, Figure 8 also shows the surface discharge PD pattern but in a scope mode in the software.

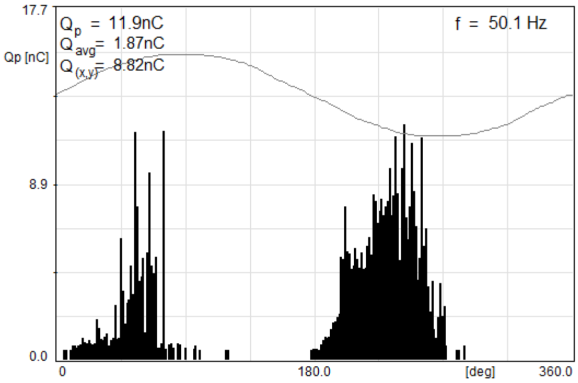


Figure 8: Surface discharge (PD pattern)

The first line analysis regarding the nature cause of the PD origin can be done by using the PD pattern. The location along the cable length has to be traced via TDR. The typical time for mapping the PRPD is 30 to 60 seconds for power frequency and around 500 to 1000 seconds for VLF at 0.1 Hz. MV class cables are typically tested in the factory according to common

IEC standards, such as the IEC 60885-3, IEC 60502, IEC 60840, and IEC 62067. The acceptance level for new cable systems is 2 pC or less. For this reason, PD events detected on MV cables under test voltage up to 1.5 times of the rated voltage are considered as a problem within the cable or its accessories.

Tan delta (loss factor) testing

Commonly used insulation materials show losses due to resistive currents or polarisation currents of dipoles. The magnitudes of these losses are usually the indicator for the quality of the insulation. Regarding the quality of aged insulation, an increase in the dissipation shows humidity or electrochemical processes, e.g., water-trees in polymeric cables or partial discharges. The software of the ICM*flex* displays the tan delta as well as the power factor, together with the calculated cable capacitance, the applied voltage, and the frequency. The loss factor values measured on MV cables are usually specified in accordance with the cable insulation system and the voltage level U_0, $2U_0$ or the tip-up between $2U_0$ and U_0. Moreover, environmental conditions strongly influence the loss factor and capacitance measurements. The following table shows typical tan delta levels versus insulation material.

Type of cable system	New	Service aged	Critical levels
XLPE	$< 0.1 \times 10^{-3}$	$\sim 1.2 \times 10^{-3}$	$> 2.2 \times 10^{-3}$
EPR	$< 3.5 \times 10^{-3}$	$> 3.5 \times 10^{-3}$	–
PVC	$< 6 \times 10^{-2}$ (50 Hz) $< 8 \times 10^{-2}$ (0.1 Hz)	$> 6 \times 10^{-2}$ (50 Hz) $> 8 \times 10^{-2}$ (0.1 Hz)	–

PD fault location

The ICM*flex* uses the TDR principle to perform fault location on MV/HV cables. For the fault location, the length of the cable and/or the pulse velocity must be known in advance. Usually, cable manufacturers provide the precise values with the cable data/report. The TDR principle is based on the travel time of pulses. Since the cable behaves as a wave conductor, the TDR principle can be used to locate the PD sources along the full cable length.

The ICM*flex* comes with a Digital Storage Oscilllo-scope (DSO) to process PD signals on a time-based curve. Single PD signals can be triggered with a time resolution of 10 ns (100 Msamples/s) and a maximum display range of 320 μs corresponding to a theoretical maximum cable length of approximately 22 km for a cable with a pulse velocity of 140 m/μs.

A PD pulse, which is caused by an imperfection within the insulation, travels to both ends of the cable. If there is an open end, each PD pulse occurring in the cable will be reflected to the opposite end when reaching one of the cable end terminations.

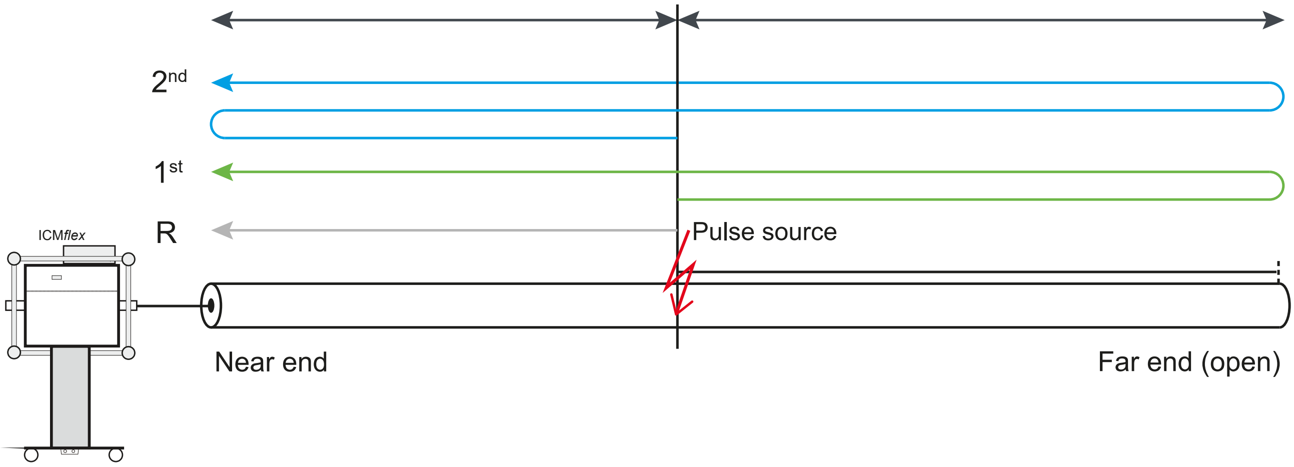
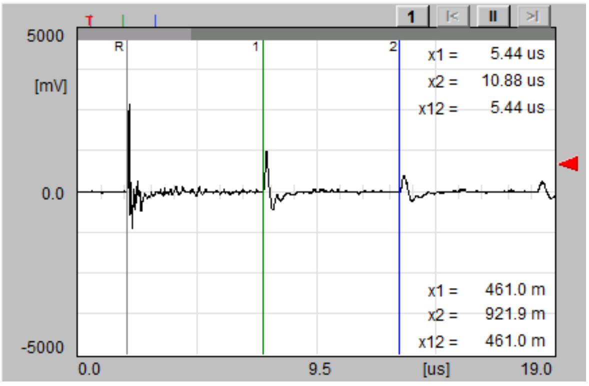


Figure 10: TDR principle

The distance of the PD source to the near and/or far end of the cable can be calculated using the time difference between the arrival times of pulses at the coupling unit. The travel paths of the first three reflections of the original PD pulse entering the coupling unit of the ICM*flex* are displayed in three different colours.



x1 = 5.44 us
x2 = 10.88 us
x12 = 5.44 us
x1 = 461.0 m
x2 = 921.9 m
x12 = 461.0 m

Figure 9: ICMflex DSO screen

The ICM*flex* DSO screen shows the reference pulse (R, black cursor), which travelled directly from the pulse source to the coupling unit. The first reflection (1, green cursor) first travelled in the opposite direction of the coupler and was then reflected at the open end of the cable. The second reflection (2, blue cursor) shows the time delay between the reference pulse and its reflection at the far end. The time delays help indicating the fault locations from near/far end.

Conclusion

PD measurement and location can be combined with portable or fixed HV sources of different principles using modern signal acquisition and processing techniques. The user-friendly interface and the easy setup of the ICM*flex* make it possible to combine measurements such as PD, voltage, capacitance, frequency, and tan delta. Moreover; it offers time domain signal analysis with 100 Msamples/s for cable fault location. All in all, the ICM*flex* is an excellent choice for MV/HV cable manufacturers and R&D researchers, who are interested in the insulation condition test of their assets.