Cost-Effective On-Line Partial Discharge Measurements for Cables

Key words: On-line PD monitoring, insulation assessment, PD location, cables.

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PD measurements for insulation assessment provide a sound scientific base for preventative maintenance and replacement planning, enabling asset managers to make informed decisions about replacing aged assets or extending their service life.

Introduction

Over ten years of development and broad on-site applications, Industrial Research Ltd. (IRL) has implemented fast, noninvasive, portable on-line partial discharge (PD) measurements for insulation assessment of various power devices [1]–[5]. Decisions as to whether repair or replacement of million dollar assets then can be made according to insulation assessments. Decisions also can be made to schedule maintenance work to suit customer or network load requirements.

The population of aged cables in many power systems is increasing at a time when there is an increasing demand for energy and improved continuity of supply. Hence, insulation failure of a cable due to partial discharge (PD) can have severe social and economic consequences. Constraints on preventative maintenance work imposed by revenue budgets and the lack of trained technicians, coupled with the need to maintain or improve supply reliability, mean that PD measurement for insulation assessment is a cost-effective diagnostic tool.

On-line PD measurements are an efficient method for detecting certain insulation defects of cables. These include defects in cable joints and terminations, which cause the most in-service cable failures in New Zealand, and defects due to mechanical impact. Noninvasive, efficient, and widely applicable portable on-line PD measurement techniques are strongly favored by the electricity industry [6]–[8]. Three on-site PD measurements for cables described in this article illustrate how the techniques achieve cost-effective insulation diagnosis to protect the main assets.

Portable On-Line PD Measuring System

The portable, on-line PD measurement system consists of proprietary clamp-on PD sensors (high frequency wideband current transformers) and a filter with a specifically selected portable digital storage oscilloscope (DSO). The clamp-on PD sensors can be either temporarily clamped or permanently installed, noninvasively in several locations at the termination of live high-voltage apparatus. These flexible, noninvasive methods of installation avoid the expense of shutting down and disconnecting the plant for testing purposes.

The sophisticated functions of the DSO allow real-time display of phase-resolved PD signals, statistical PD signatures (such as PD levels) phase positions and occurring frequencies that are distinct from noise. Locating PD sources becomes simpler and more accurate with the clear identification of an incident PD pulse and its reflection using a 2.5 GS/s sampling rate DSO. PD location is essential when large dangerous PD is detected.

Applications to Distribution Cables

After a series of four cable failures, on February 20, 1998, the power supply to the Auckland Central Business District was cut off for over a month. The Auckland power crisis raised awareness of the importance of cable reliability. This event has now challenged electricity network operators to ensure the reliable operation of numerous widely located distribution cables, especially when many of them are over 30 years old. The reliable performance of these cables is essential for industrial and domestic electricity users. Merely replacing cables that have reached a certain age limit is not practical from an environmental, manpower, or economic perspective. Cable defects need to be identified, located, and repaired before failing in service. This should be done in the most cost-effective way.

For installed cables, installing PD sensors in cable joints or terminations can hardly be justified by their operators or owners. The wide variance of cables, terminations and joints also makes it difficult to noninvasively place on-line PD sensors. Figure 1 shows several practical, noninvasive options for attaching clamp-on PD sensors to cables that are in service.

On-site experiences showed that placing the clamp-on PD sensor on a cable screen ground at a cross-bond joint achieves the best signal/noise ratio. Alternatively, the sensor can be placed at the cable termination ground end. The noise usually is highest when the sensor is placed on the cable screen ground; nevertheless it is often more convenient for on-site applications. Selecting a PD sensor position and frequency band of the filter are initial steps for an on-line PD measurement of high signal/noise ratio.

Phase-resolved PD measurements are carried out to check if there is PD in a cable and to determine the PD level in each phase. PD location by time-domain reflectometry measurements then is performed to decide if the measured PD pulse is inside the cable or if it is external corona or noise from the cable terminations.

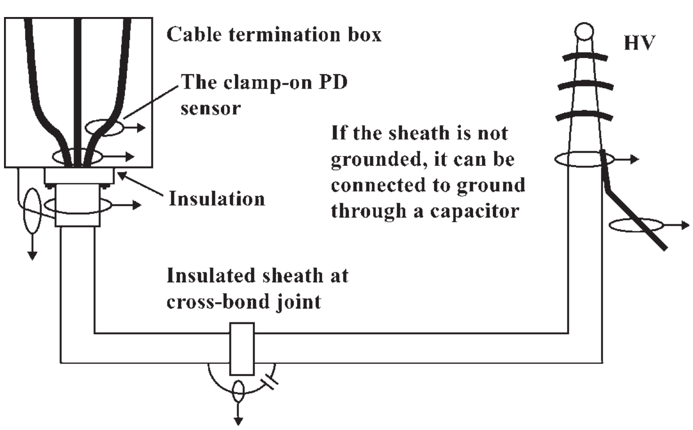

Figure 1. Possible positions to non-invasively place a PD sensor for on-line PD measurement and location.

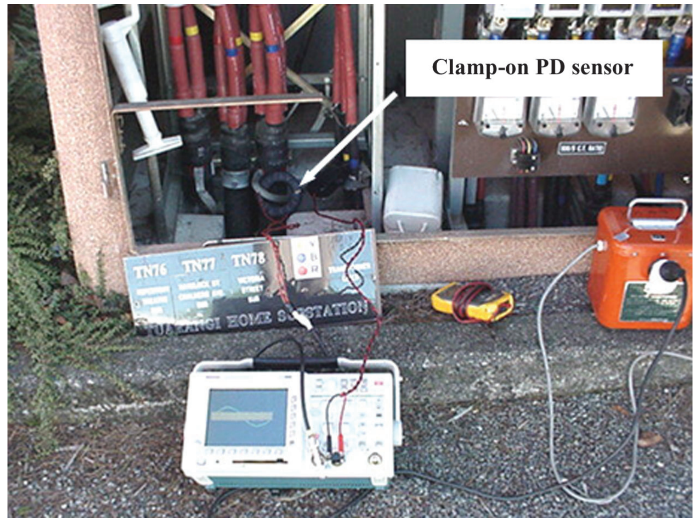

Figure 2. The on-line PD sensor was placed on screen earth lead.

A. On-Site Application Case #1—More Informative Results from Both On-Line and Off-Line PD Tests

With three successive joint failures in a week, a company requested PD tests for insulation assessment of the cables concerned.

For the on-line PD measurements, the PD sensor was placed at the cable termination earth end or screen earth at the cable termination box of ring mains switch as shown in Figure 2. Corona discharges at cable terminations were detected and proved by both PD location and an ultrasonic detector, which can pinpoint the corona spot.

Because these cables could be isolated easily by ring-main switches, off-line PD measurements also were carried out for more informative results. The off-line PD tests, shown in Figure 3,

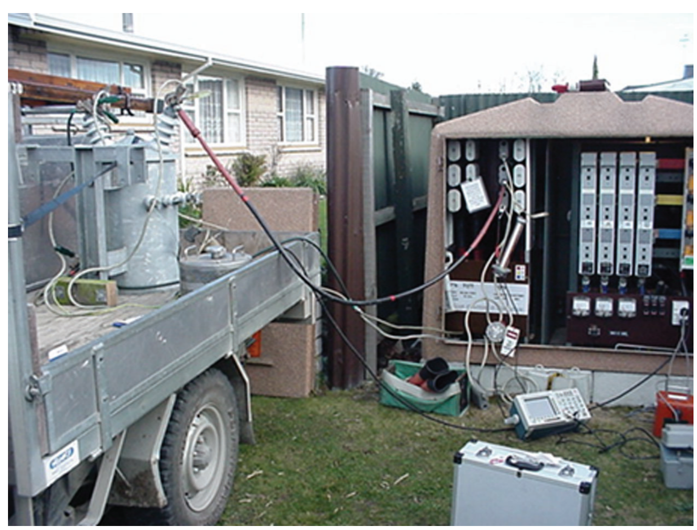

Figure 3. The off-line PD measurement for an 11 kV cable.

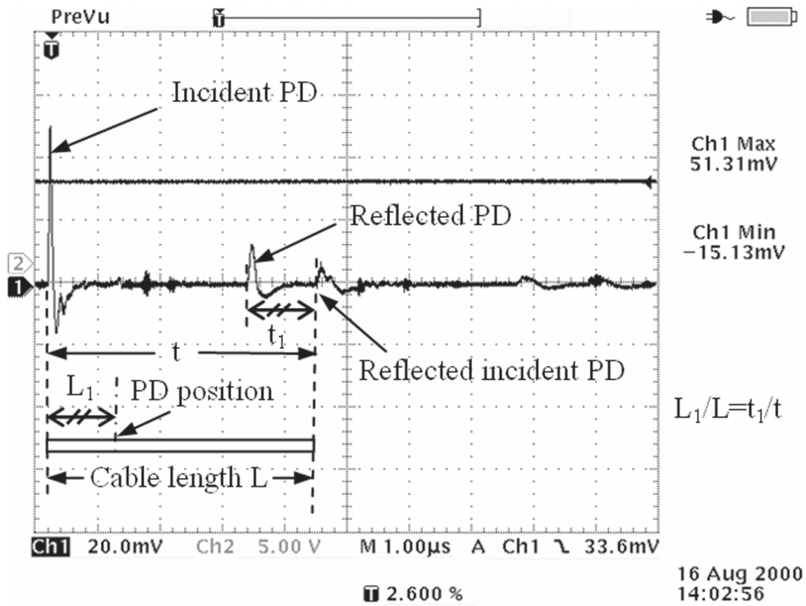

Figure 4. The PD location L_1 is $L \times t_1/t$, or $v \times t_1/2$ (v is PD propagation speed).

found that a joint had PD at 7.5 kV, which was 1.2 U_o. PD location in Figure 4 indicates that the PD was in the joint at 25.6% of the cable length, L, from the test end.

The joint was found to have PD and was replaced accordingly. The client was cautious and also decided to install a permanent PD sensor on a crucial 33 kV cable for more frequent PD monitoring. This case showed that both on-line and off-line PD tests provide more informative results. The higher test voltage can reveal defects that may not show under operating voltage. For many short cables (less than 500 m) that can easily be isolated by ring main switches, both on-line and off-line PD tests can be achieved easily with the portable on-line PD measuring system.

Table 1. PD levels at PD inception and other voltages

Tested phase	Red	Yellow	Blue
Inception voltage			
(kV, rms)	31.8	21.2	31.8
PD Max (mV)	4300	184	2300
PD Max (pC)	5059	212	2706
Test voltage V			
(kV, rms)	35.4	35.4	42.4
PD Max (mV)	4740	2370	2440
PD Max (pC)	5576	2788	2871

B. Onsite Application Case #2—AC On-Line PD Results versus 0.1 Hz Off-Line PD Results

PD tests for a 2.1 km, three core, 33 kV cable were conducted as commissioning tests to detect if there was PD due to suspected

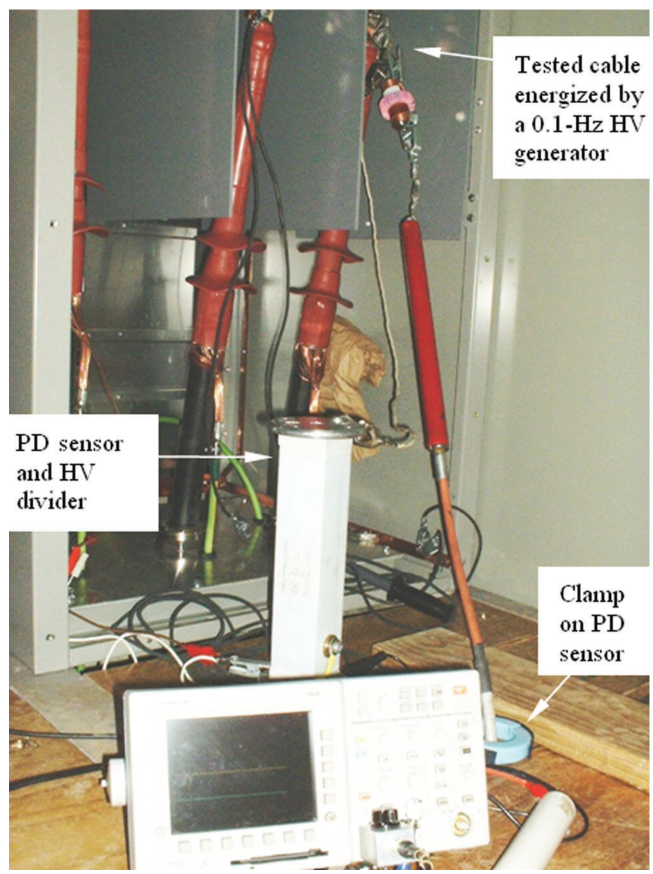

Figure 5. The test set up for off-line PD measurements.

Figure 6. A PD sensor was placed at the link that short-circuits the cross bond

mechanical damage during installation. The suspected mechanical damage was caused by excessive pulling force on the cable when this section of cable was pulled around a sharp corner in a cable duct. The company hired a 0.1 Hz VLF generator to energize the cable for the off-line PD tests. An on-line PD test also was carried out to compare the test results for more informative insulation assessment.

Energized by a 60 kV (peak) low-frequency generator, the PD test set-up is shown in Figure 5. The PD and noise identification were based on checking each PD pulse-by-pulse method, which compared every captured PD pulse from the two PD sensors, then deciding if it was a PD or a noise pulse. PD fault location by PD incident and reflection further confirms whether it is PD in the cable or external noise. PD levels are shown in Table 1.

All large PDs shown in Table 1 were external corona discharges on the cable termination at the test end. The corona discharges were due to the 0.1 Hz power supply, which changed the capacitive and resistive electric field distribution of the cable termination. These external corona discharges have a much less damaging effect than the PD from cable insulation. PD from the cable insulation and joints, which often causes cable insulation failure, is the main concern.

As PD signal attenuates when propagated through a long cable, on-line PD measurements were carried out at both cable

Table 2. On-line PD levels

Phase		Red	Yellow	Blue
PD at substation end	(mV)	4.5	26.4	3.4
	(pC)	113	660	85
PD at X-bond I	(mV)	9.1	11.0	9.4
PD at X-bond II	(mV)	6.0	7.1	6.4

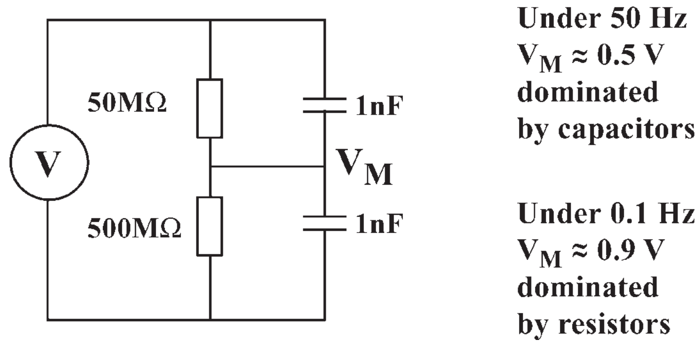

Fig 7. Capacitive and resistive voltage distributions at 50 Hz and 0.1 Hz

terminations and at two cross-bond joint screen grounds, on a 2.1 km long cable. This gave high-sensitivity PD measurements. At the substation end, the clamp-on PD sensor was placed on the ground lead of the cable termination while the system was energized. At the cross-bond of the cable joint, the PD sensor was clamped on the temporary direct short link at each cross-bond of the cable joint as shown in Figure 6. The PD level measured at each position and phase is listed in Table 2.

The yellow phase at the substation end had the highest PD level, which was over five to seven times higher than that of red and blue phases, respectively. The PD was from the substation end cable termination (PD is often detected from 33 kV cable terminations shortly after installation).

PD location by PD incident pulse and its reflection proved that no PD arose from the cable insulation as a result of suspected mechanical stress during installation. This confirmed that the cable insulation is sound and eliminated the owner's concern. The condition of the cable terminations and joints also were assessed from the PD test results, and a future monitoring program was suggested.

Comparison of the on-line and 0.1 Hz PD test results showed that they did not correlate in PD level or in PD inception voltage. The PD level measured on-line was the highest for yellow phase, but it was the lowest in the 0.1 Hz PD measurement. The PD inception voltages from the 0.1 Hz measurements indicate that there should be no PD at operating voltage, but this was not found to be true. Why were the PD performances at 50 Hz and 0.1 Hz different? This was likely due to the different electric field distributions in the cable termination at the two different frequencies. This is illustrated by a simple capacitors and resistors circuit in Figure 7.

This case showed that, although a 0.1 Hz generator provides an efficient high-voltage power supply for on-site testing of long cables, the PD detected under 0.1 Hz might not happen under 50 Hz.

C. Onsite Application Case #3—High Sensitivity On-Line PD Measurements for Long Cable with Cross-Bonds

The objectives of the on-line PD measurement and location for the 5.3 km, 33 kV cables were to assess the insulation and to

Figure 8. PD sensor was clamped on the cross-bond earth

Table 3. PD levels at substation end and each cross-bond (←S, towards substation, →F, towards far end)

PD Measured at	PD level (Max mV/ Min mV) Red phase		PD level (Max mV/ Min mV) Yellow phase		PD level (Max mV/ Min mV) Blue phase	
	←S	→F	←S	→F	←S	→F
Substation end	+6.2/ −10		+7.3/ −9.8		+4.1/ −5.2	
X-bond 1	+2.2/ −3.7	+5.1/ −4.0	+2.8/ −5.2	+5.0/ −6.5	+7.5/ −7.6	5.0/ −3.9
X-bond 2	+8.5/ −9.0	+12/ −12	+13/ −5.0	+12/ −12	+8.5/ −11	6.5/ −12
X-bond 3	+90/ −59	+60/ −95	+18/ −37	+26/ −20	+14/ −35	+17/ −16
X-bond 4	+56/ −95	+61/ −59	+60/ −95	+34/ −79	+55/ −25	+44/ −34
X-bond 5	+15/ −14.5	+17/ −18	+14/ −12	+23/ −14	+14/ −15	+13/ −19

establish the PD signatures. The PD tests were carried out before and after a civil construction project near the cable to compare the test results in order to determine if there was any PD due to possible damage from the construction project.

The three single-core cables had 17 joints and 2 sets cross-bond earths. The cable screens were directly grounded at the substation end, cross-bonded at joint 3 (cross-bond No. 1), joint 6 (cross-bond No. 2), and directly grounded at joint 8, then cross-bonded at joint 11 (cross-bond No. 4), joint 15 (cross-bond No. 5), and directly grounded at the far end overhead termination. The PD signal attenuation and cross talk between phases for the long cable with cross-bonds were challenges for the on-line PD measurements.

The on-line PD measurements were taken at the cable termination in the substation switchboard end and at every cross-bond ground, in order to achieve high sensitivity for every section of the cable between the cross-bonds. After checking the currents and voltages of the cross-bond ground while the cable was in normal operation, the PD sensor was clamped on the cross-bond ground (Figure 8).

Both phase-resolved PD measurements for PD levels in each phase and PD location for each discharge pulse were recorded to determine on which phase the PD occurred and where the discharge was located. The PD position, in terms of distance to the cross-bond where the PD was measured, was determined by the PD locations at the two cross-bonds of the section of the cable to provide two alternative measurements of the PD position.

A typical phase resolved PD measurement (16 acquisitions) for the red phase at cross-bond 3 is shown in Figure 9. This measurement detects if there is PD and on which phase the PD occurs. The AC reference was the current of the screen ground, which had a phase shift to the phase voltage. The PD levels measured for each phase at each cross-bond are listed in Table 3.

Though various PD levels were measured at each cross-bond joint, PD fault location showed that relatively large PD (estimated at a few hundred pC) was from the red phase of section X3-X4. The PD location was at 82% of X3-X4 from X3 end or 18% of X3-X4 from X4 end. This was confirmed by PD locations from both X3 and X4 joints. The PD location measurements at X3 and X4, the timing of the PD incident and reflection pulses to calculate the distance are shown in Figures 10 and 11.

With the given length of X3-X4 1138 m, the calculated PD location to X4 is 205 m. The given distance between joint 10 to joint 11 (X4) is 206 m, the ratio of 206/1138 m is 18.1%, indicating that the PD location is most likely at joint 10.

The cable joint consisted of three layers of heat shrink sleeves. The large PD was likely to have occurred between two layers not bonded tightly as shown in Figure 12 (a similar type joint from another cable).

As the PD level is relatively high, a joint kit for this joint can be prepared in case the joint fails in the near future. With the preparation and known PD location, the recovery after a failure would be much easier than being unprepared for the cable failure. Further confirmation of the PD location by excavating the joint, testing by an ultrasonic probe at the suspected joint and replacing it before it fails in operation, and a monitoring program were also suggested.

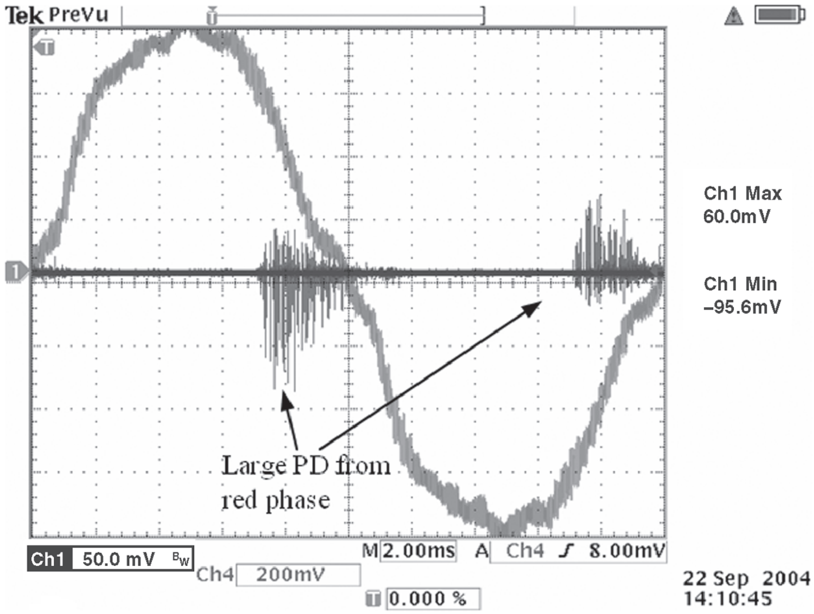

Figure 9. Phase resolved PD measurement for the red phase at cross-bond 3 (phase reference was the capacitive current at the cross-bond)

This case showed that, for long cables with cross-bonds, high-sensitivity PD measurements can be achieved at cross-bond grounds. PD measurements at all cross-bond grounds and PD fault locations at both sides of each section between the cross-bonds provide confirmative results. The uncertainty of PD location due to cross talking through cross-bond can be resolved by evaluation of all measuring results at each cross-bond.

Conclusions

The extensive on-site applications illustrated in this article have demonstrated the following advantages of the portable, on-line PD measurement system.

- Noninvasive, fast, and cost-effective insulation assessment and monitoring.
- Does not degrade the insulation.

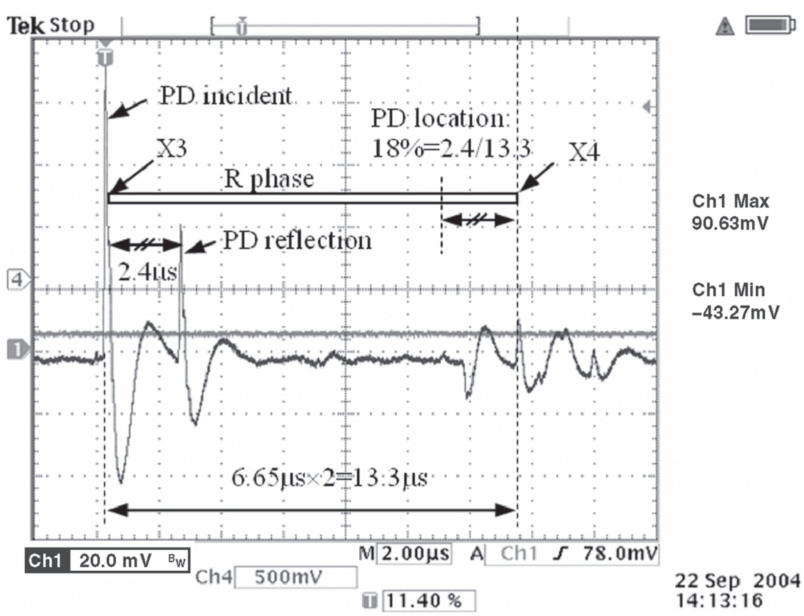

Figure 10. PD incident, reflection pulses and location measured at X3

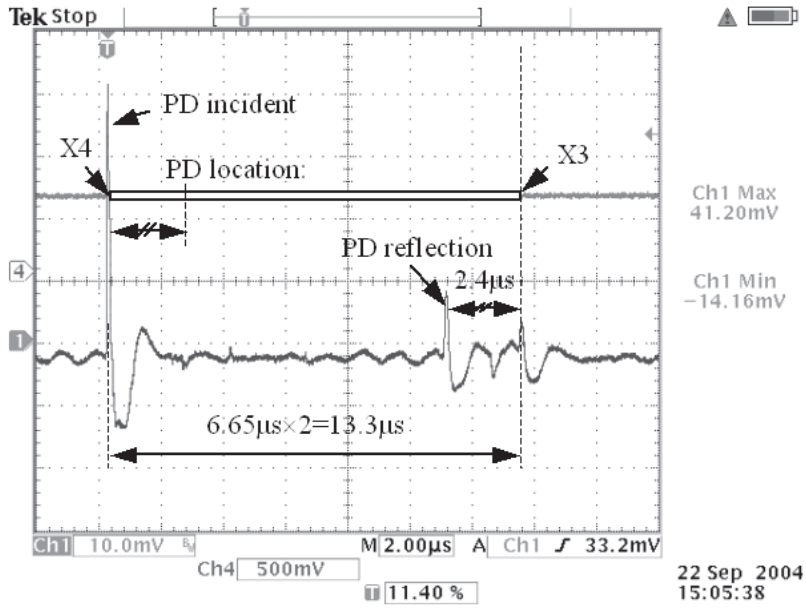

Figure 11. PD incident, reflection pulses and location measured at X4

- Suitable for a broad range of cables.
- Minimum or no power interruption.
- Various PD measurements and displays give informative and reliable insulation assessment.
- Easy to use and facilitate the understanding of the PD characteristics.
- Simple and accurate PD location.

The PD measurements for insulation assessment provide a sound scientific base for preventative maintenance and replacement planning. This enables asset managers to make informed decisions whether to replace aged assets or to extend their service lives. By identifying and quantifying PD performances, the reliability of power systems can be enhanced through appropriate remedial actions.

Figure 12. PD burn marks between two layers of sleeves of a joint

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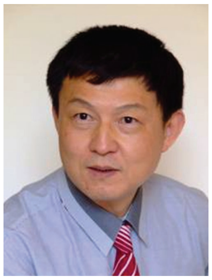

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