First Field Experience of On-line Partial Discharge Monitoring of MV Cable Systems with location

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ABSTRACT
A new measuring system is presented for the on-line monitoring and location of partial discharges (PDs) in medium-voltage power cables. The system uses two inductive sensors, each at one cable end. The measuring system is called PD-OL, which stands for PD detection On-line with Location. A pulse injection system is used for the time synchronization of the data intake at both cable ends and for the on-line calibration. PD data is send via internet to the KEMA Control Center for interpretation and final presentation, made visible on a secured web-site for the network owners. This paper discusses the basics of PD-OL and a number of measurement results.

INTRODUCTION
Many grid owners indicated the need for an on-line PD monitoring system, i.e. while the cable connection remains in-service. This need has been expressed already for years, both for hv and mv cables.

For hv cable circuits (≥ 50 kV), PD monitoring solutions have been introduced, based on sensors per accessory. This is unpractical for mv cable circuits (≤ 36 kV). Therefore, in case of mv cable connections it is much better to work with only two sensors, one at each cable end. With two sensors one can cover the whole cable connection indeed, simply by measuring the difference in arrival time at both sensors. The sensitivity of such a measuring system can be compared with the well known off-line PD measuring systems for mv cables. Such an on-line PD measuring system works for all types of mv cables (e.g. XLPE insulated, paper insulated) and all types of accessories installed.

So far, this approach sounds simple. However, until 2005 this was not really available. One of the problems that had to be solved was the synchronization of both sensors at the cable ends. After a couple of years of research activities [1], [2] a prototype of a measurement system became available. At the CIRED 2005 conference, the basics of the PD measuring system called PD-OL, was fully presented for the first time [3]. PD-OL stands for Partial Discharge testing On-line with Location. PD-OL is protected by a patent [5].

Since its introduction, energy was spent in realizing commercial equipment, which arrived in 2007. Approximately 120 PD-OL systems based on this have been put in operation since that time. Some of the principles, together with some results after one year of operation are shown in this paper.

This introduction of this paper is partly similar as in the paper presented at the CEPSI in 2008 [6]. For this CIRED 2009 paper the focus is mainly on new examples of measuring results which can be find in the second half of this paper.

PD-OL MEASUREMENT SYSTEM SET-UP
One PD-OL system consists of two separate PD-OL measurement units, each of these to be installed at one of the cable circuit ends in either substation or RMU(s) (Ring Main Units). See for an illustration Fig. 1.

Fig. 1  PD-OL installation, with at each cable end a control unit (PD-OL - CU) for signal processing and communication via internet and a sensor/injector unit (PD-OL - SIU) for the actual measurement and pulse injection.

Each measurement unit consists of:

a) A sensor/injector unit (PD-OL - SIU). As the name suggests, this unit contains both a sensor, to measure pulses from the cable, and an injection device, to inject pulses into the cable. This unit can be split in two parts and in this way clamped around the cable or cable earth connection, which all can be done on-line.

b) A controller unit (PD-OL - CU), which is connected to the SIU by means of an optical fiber. The controller unit (which is in fact a small dedicated computer) controls the measurement sequence, the data collection and the signal processing. It has also communication facilities on board (LAN, modem or mobile phone /
GPRS card) in order to upload the resulting data via the internet to the Control Center at KEMA for further interpretation. Furthermore, in this way, the PD-OL units can be reached via the internet for diagnostic purposes and updates. All is performed automatically and remotely, so once installed no physical access to the units is needed.

**PD-OL MEASURING SEQUENCE**

Power cables in an on-line situation are in many cases connected to a next cable. Therefore, PD pulses do not reflect at all or only to a minor degree. Furthermore, in an on-line situation, also PD alike pulses from adjacent equipment arrive at the sensors. In order to discriminate PDs from the cable under test from other pulses and to locate their origin, it is necessary to apply sensors at both sides of the cable circuit, which is the chosen solution with PD-OL. That simple fact implies that the PD-OL - CUs installed at both cable ends do need some trick to get in time synchronization with each other. The patented solution [5] is that via the PD-OL - SIUs not only PDs can be measured, but also pulses can be injected via an inductive coil (e.g. once every minute). This pulse injection at the master PD-OL - SIU is the accurate starting time of measuring PDs. The slave PD-OL - SIU at the other cable end will start doing the same immediately after receiving this injected pulse, which is exactly the cable propagation time later. Since the propagation time of the cable is known, accurate time synchronization between the two PD-OL units has become possible. Advanced signal processing techniques ensure that this method achieves sufficient reliability and accuracy.

This sequence results in time-synchronized records of data. In the control unit this data is correlated with matched filter banks in order to judge whether the measured data contains PDs. Resulting from this signal processing are tables of detected PD pulses from both cable ends. Not the complete measured waveforms, but only these (much smaller) resulting tables are then communicated over the internet to the Control Center at KEMA. In this Control Center the results from both cable ends are combined, which leads to both the elimination of pulses from other sources and the determination of the location of the PD spot.

There are several criteria that help to eliminate other disturbing pulses and select whether a pulse is indeed a valid PD pulse, being discussed in detail in [4]. Also other particular features of the PD-OL measuring system are discussed extensively in [4] like the sensors applied, the best sensor locations, calibration matters and noise suppression. In [4] also other references are mentioned, discussing these items in more depth.

**FIELD PD RESULTS**

Since various measurement systems have been installed during the year 2007 and 2008 and lots of measurement results can be presented now. To do this, various presentation forms are chosen in order to show the benefits of doing the PD measurements on-line.

**Example Circuit A**

The first result presented here originates from a cable circuit A. The Paper Insulated Lead Covered cable circuit length is 143 m. For illustration, only an 8 day period is shown from a much longer measuring period in Fig. 2. The PD activity is very clearly varying with time; it follows the day-night load cycles, resulting in 8 clear PD concentrations with quiet periods in between.

![Fig. 2 3D plot of measured PDs from circuit A. The top vertical axis on the left side is charge (pC), the bottom left vertical axis is the location along the cable length (143 m) and the horizontal axis is time, which is in total ca. 8 days.](image)

**Example Circuit B**

In Fig. 3 results from PD-OL measurements from another circuit B (2100 m in length) with Paper Insulated Lead Covered cable are shown after 4 months of measurement. Besides the increase of activity in the other cable locations and the increase in magnitude of the PDs from the 1364 m joint, a completely new PD concentration of large magnitude and high concentration has become visible. Apparently, a new weak spot, next to the 1364 m joint, has arisen, which was not or hardly visible in the first 3 months. In Fig. 4, the 3D graph of the same measurements is shown. In this graph a clear increasing trend in PD magnitude at the 1364 m joint location is shown. The PD magnitude level as such is not dangerous yet, but if this trend of increasing PD magnitude remains, degradation is very likely to exist and high risk levels can be reached. It is such trends that are visible now and will most probably help us a lot in the interpretation of these PD graphs, resulting in risk levels and remaining life estimations.
Fig. 3 2D graph of PDs measured in a 2.1 km long circuit B after 4 months of measurement time.

Fig. 4 3D graph of PDs measured during 4 months on circuit B. A clear increasing trend in PD activity from the fluid-filled joint at 1364 m is visible.

Example Circuit C
In Fig. 5 the 3D graph shows also here an increasing PD trend in a resin joint at 173 m, located in a Paper Insulated Lead Covered cable with a circuit length of 537 m. The network owner is now planning to replace this joint.

Fig. 5 3D graph of PDs measured during 4 months on circuit C with a clear increasing trend in PD activity from the resin joint at 173 m.

Example Circuit D
In Fig. 6 the 3D graph shows concentrated PDs from a resin joint that failed during a withstand test. The test was applied and the joint broke down, proving this joint was indeed not fit for use anymore. After this testing the cable was out of service during a few days, after which the new joint was PD free (as can be seen in Fig. 6).

Fig. 6 3D graph of PDs measured during 1 month on circuit D with clear PDs from a resin joint that failed during a withstand test.

Example Circuit E
In Fig. 7 the 3D graph shows concentrated PDs from a heat shrink joint that failed. The joint was located at 1678 m in an XLPE insulated cable circuit of 4258 m long. The network owner was recommended in time to replace this joint but unfortunately, the wrong joint (at 1801 m) was replaced after which the PDs did not disappear of course and a bit later the cable failed on the identified joint location at 1678 m. Anyhow, the replacement recommendation was correct.

Fig. 7 3D graph of PDs measured during almost 1 month on circuit E with a clear increasing trend in PD activity from a heat shrink joint at 1678 m that failed.

Example Circuit F
In Fig. 8 the 2D graph clearly shows concentrated PDs at three different locations in the XLPE insulated cable of
7058 m length. The PD's were collected over a period of almost one month. This was a curious observation because the PD locations were far away from joint locations. The network owner inspected the cable at these PD sites and discovered that over large lengths, the earth wire screen of the XLPE cable was burned away, due to too high fault currents in the copper wire earth screen, see Fig. 9.

CONCLUSIONS

Compared to off-line PD diagnostics, PD-OL is seen as a step forward in diagnosing MV power cables. In summary the advantages are:

- installation for network owners anywhere in the world
- on-line installation, sensors without galvanic contact
- PDs seen under normal service conditions and can be monitored continuously, making trends, variations and short-duration PD activity visible
- all PD data is automatically uploaded via internet for interpretation to one place in the world where expertise is concentrated
- hourly update of PD maps and interpretation results for all network owners via internet.

REFERENCES


MISCELLANEOUS

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