ON-LINE PARTIAL DISCHARGE DETECTION OF MV CABLES WITH DEFECT LOCALISATION (PDOL) BASED ON TWO TIME SYNCHRONISED SENSORS

Peter C.J.M. VAN DER WIELEN [*], **Jeroen VEEN** [*], **Peter A.A.F. WOUTERS** [**], **E. Fred STEENNIS**[***]
[*], [**] **Technische Universiteit Eindhoven – the Netherlands,** [***] **KEMA – the Netherlands**
[**] **p.a.a.f.wouters@tue.nl** , [***] **fred.steennis@kema.com**

INTRODUCTION

A new and unique measuring system is presented for the on-line acquisition and analysis of partial discharges (PD-s) in medium-voltage power cables. The system is able to locate the origin(s) of PD-s by using two inductive sensors, each at one cable end. The measuring system is called PDOL, which stands for PD detection On-line with Localization. A patented solution is used for the time synchronization of the data intake at both cable ends and for the on-line calibration. One computer at a remote location collects data from various PDOL measuring systems for final presentation and interpretation. This paper discusses the basics of PDOL and some first measurement results.

THE BACKGROUND OF THE MEASURING SYSTEM PDOL

PD measurements are a well-known way to diagnose medium-voltage cables. Applied nowadays are off-line test systems that both can measure and locate PD-s based on one sensor at one cable end and PD pulse reflection [1]. It implies that the cable has to be disconnected from the grid and energized with a separate power supply in order to generate the PD-s.

One can question, why these PD-s are not measured on-line. The main reason is that under on-line conditions PD pulses will hardly reflect at the cable ends anymore, making localization with one sensor practically impossible. The reflections have become (too) small because of the similar impedance of the equipment connected to the cable under test in an RMU (Ring Main Unit).

For on-line PD detection and localization, the only effective solution is placing sensors at both cable ends as is illustrated in the basic set-up of PDOL in Figure 1. As such, this solution looks simple. But there is a new problem now. It requires accurate time synchronization of the digitizers at both cable ends. In case of a required PD localization accuracy of about 1 % of the cable length, the related time synchronization of the digitizers should be in the order of 100 ns in case of a 2 km long cable (assuming a pulse velocity of 200 m/µs). For this synchronization there is a known and patented solution with GPS [2]. However, this is an expensive and unpractical solution for long-time diagnostics. A possible alternative, as suggested by many people, is the use of atom clocks. But these are either not stable enough, or even more expensive. The now presented measuring system PDOL uses pulse injection for synchronization. On a regular basis, pulses are injected at one cable end and measured at both cable ends. Pulses are injected with an additional coil along the measuring sensors in the RMU-s, see Figure 1. This way of synchronization is cheap and very effective, as will be shown. The pulse injection method is a crucial and patented element in PDOL [3].

The sensors applied in PDOL are inductive sensors. These are cheap and easy to install, two important advantages. Such sensors however have disadvantages too. In the first place, in general inductive sensors placed in an earth lead will pick up more noise / interference than capacitive sensors would do. This will be treated later in more detail. Secondly, they can only be applied in a so called open RMU. This is an RMU where the metal screen at the cable end has a separate earth lead (a path for the PD pulse) to the general grounding system as in Figure 1. In a closed RMU, where the metal enclosure of, for instance, the switchgear is fully bonded with the metal screen of the power cable, such an attractive location for an inductive sensor cannot be found. Since PDOL is based on inductive sensors (at the moment), it is a measuring system that is optimized for open RMU-s.

Before a PD can be measured, it is important to calibrate the system. In PDOL a smart solution is applied. At each cable end, steep pulses are injected, which are measured separately at both cable ends, see Figure 1. The amplitudes and shapes of the resulting signals that are measured with the inductive sensors depend on the impedances of the power cable under

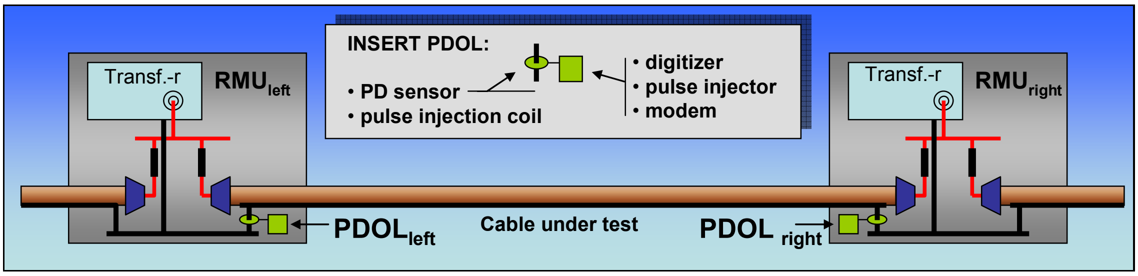

Figure 1 PDOL measuring system, basic set-up for a power cable between two RMU-s.

test and the connected RMU-s. In this way, the transfer impedance for a pulse coming from the power cable and entering a sensor can be calculated. This information is used for the actual calibration of PDOL. Again, the patented pulse injection method is crucial here too.

PD data acquisition is carried out at both cable ends. There, the first step of the data analysis is done in order to extract possible PD signals from the noisy data, remove clear interfering signals and thereby reduce the size of the data to be communicated. The resulting data is sent by LAN or modem and telephone connection to a server. Here, the final PD map is made, based on PD-s and their time on arrival. Since PDOL is acting on-line, this map can be presented as a function of time and other cable parameters such as cable load, etc.

ADVANTAGES OF THE MEASURING SYSTEM PDOL

Compared to off-line PD diagnostics, PDOL has the following advantages:

- permanent monitoring possible, PD trend watching
- possibility to find defects with PD-s only a short time before breakdown (months, weeks or even hours)
- on-line calibration (for instance once per hour)
- cheap equipment
- easy installation
- remote data collection via the web

THE MEASURING SYSTEM IN DETAIL

Sensors

For measuring partial discharges on-line at the cable terminations, the choice and design of the used sensor is crucial, not only for technical demands like sensitivity and bandwidth, but also practical requirements should be met. The sensor must be installed in an existing network, preferably during operation and may not introduce a safety risk during installation or operation. The use of inductive toroidal sensors has some important advantages [4]:

- the sensor (especially those that can be clamped around a lead) can be mounted without de-energizing the cable,
- toroidal coils measure the total enclosed current and are therefore hardly dependent on the geometry of equipment in substations or RMU-s,
- no galvanic contact is made, so the sensor itself can never become a cause of power failure itself.

Sensors that meet the required sensitivity ($V_{out} / I_{in} \approx 1\ \Omega$) in the required bandwidth (about 100 kHz − 30 MHz) are commercially available, usually with a split-core of ferro-magnetic material. Core material is used to increase the sensitivity of the sensor. To avoid saturation, caused by for instance the power-frequency current, an air slit is usually introduced, which coincides with the probe's clamping mechanism. With the correct design, however, air coils can also provide for sufficient sensitivity [6]. The advantage of air coils is that they cannot saturate and they can relatively easy be constructed without too much mechanical difficulty. Shielding, however, is usually also necessary, since the sensors are installed in substations and RMU-s, in other words, in environments with high electro-magnetic disturbance. Easy construction of an air coil can be retained by establishing the shielding with the use of coaxial cable as windings of the coil [6].

Another aspect of PD signal detection with sensors at the cable terminals is the positioning of the sensors.

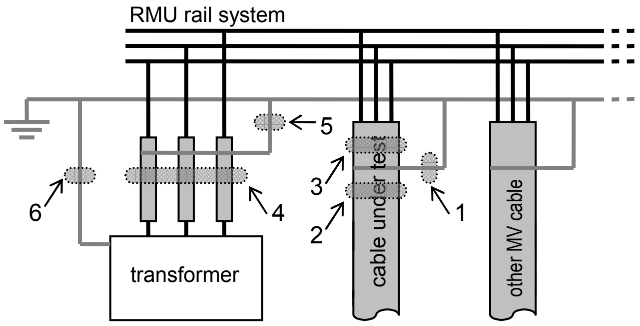

Figure 2 Possible sensor locations in a typical RMU.

Figure 2 shows a schematic drawing of a typical RMU layout with indicated possible sensor positions. These possible sensor positions with their advantages and disadvantages are described below:

1. Currents in the shield of the cable under test will propagate through the (last) earth strap at the termination. This location, however, also includes (common mode) currents which return via some other (always present) earth path and introduces therefore additional noise. Measurements have validated this [4].
2. Location 2 incorporates both the forward and return current of a possible PD signal, resulting in a total current of zero.
3. Location 3 is the preferred location, since only signals from the cable are measured, while safe installation is possible due to the shield of the cable.
4. The PD current from the cable will distribute over the several impedances in the substation [5]. If a distribution transformer is present in the substation or RMU, its current can be measured safely around the power cables to this transformer if these cables are shielded.
5. Since these cables to the transformer are relatively short, they can be modeled as lumped-circuit capacitors [5] and the PD current though these capacitors can be measured at location 5.
6. Location 6 is drawn as a single connection in Figure 2. However, in practice, high frequency PD currents will find other paths as well, making this location less attractive for measurements.

Since a sensor at location 3 measures signals from the cable under test before distribution over multiple impedances, this is usually the preferred location. Since location 5 provides for a measurement of the PD current through an impedance (capacitance), it is in principle a PD voltage measurement over this impedance. This is the same voltage as the voltage over the cable under test. If both the PD current and its voltage are measured, the propagation direction of the PD pulse is determined. This combination of location 3 (or alternatively 1) with location 5 provides therefore for a powerful tool to discriminate between pulses from the cable under test and signals from other sources [6].

Synchronization

In order to locate PD-s within 10 to 20 m, the time-bases of the measurement units have to be related within a margin of about 100 ns. In [7] a method is presented to align time-bases of multiple measurement set-ups for off-line PD detection of long and branched cable systems. The applied GPS system for synchronization is already being used for several years, and results are satisfactory. Another patented option is to synchronize measured data by means of pulse injection [3]. If pulses are injected at one cable end and measured at the other side, the time bases can be synchronized to these pulses. This technique has a number of important advantages. The power cable itself is used as transmission medium. This channel is well defined, definitely present and insensitive to external influences (like buildings, weather, etc.). Moreover, less expensive equipment is needed, since the coupling to the cable can be established with coils similar to the measurement sensor(s).

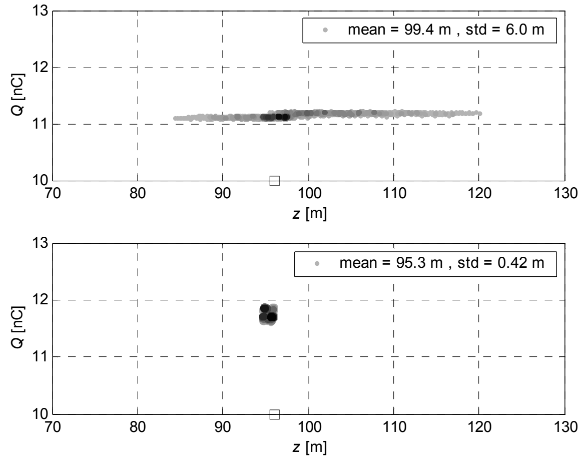

Figure 3 Measured pulses, originating from a joint at 96m and located using GPS synchronization (top graph) or pulse synchronization (bottom graph).

Several measurements have been conducted to evaluate the accuracy of the different synchronization methods (see also [6]). Figure 3 shows a (zoomed) mapping diagram of pulses, measured at a 300m cable connection with the PD on-line system PDOL, synchronized with GPS and with pulse injection. The pulses originate from a joint at 96m. The mean and standard deviation of the location results are indicated in the figure. It is clearly seen, that the pulse injection method outperforms the GPS synchronization. The accuracy of GPS is partly independent of the cable length, since factors like satellite visibility, atmospheric conditions, etc. influence the accuracy. The accuracy of the pulse injection method decreases more strongly with increasing cable length (approximately inversely proportional). Measurements in [6] show, that for a cable length of about 8 km, both synchronization methods produce similar results (location deviation of 0.2% of the total cable length). The method of pulse injection, however, still has the mentioned practical and economical benefits. Pulse injection is therefore the synchronization tool in PDOL.

Data acquisition

In off-line measurements, PD signals can be detected utilizing a digital storage oscilloscope, which triggers on signals that exceed a pre-set threshold. Generally, narrow-band periodic disturbances resulting from radio broadcasts or communications dominate on-line measurements. Interference amplitudes may be higher than PD signal amplitudes, illustrated in figure 4. Therefore data acquisition triggered by PD signals is generally not feasible. Moreover, disturbances may vary with time and among measurement situations; therefore the application of analogue pre-filters is very limited, since they should automatically adapt to the situation at hand. For these reasons, a block-based approach is chosen for the measurement system PDOL, i.e. long data blocks are repetitively acquired and analyzed, instead of data acquisition triggered by PD signals. In addition, since interference amplitudes may be much higher than PD amplitudes, a 12-bit digitizer was chosen in order to increase the dynamic range of the system, such that small PD signals can still be acquired with sufficient resolution. In principle, only a small percentage of discharges has to be detected for the purpose of on-line power cable diagnostics, since in the long term enough PD signals can be extracted to enable defect characterization. Consequently, a relatively large processing delay (in the order of 1 min) is acceptable for each data block (in the order of 20 ms). In conclusion, the measurement system PDOL offers semi-continuous, block-based data-acquisition.

If large data sets are recorded, the digitizer sample clocks may deviate during acquisition. It can be assumed that the difference between the sampling clock frequencies at both ends changes slowly with time. With sensors at both cable ends, this deviation can result in errors in the determination of the difference in time of arrival of PD signals, and therefore in localization errors. To correct for time-base wander, two synchronization pulses are injected in each data-block, one at the beginning and one at the end [6], [10]. If the exact time delay between the two pulses is known, the time difference in the recorded data should represent this time. The difference between the exact time delay and the interval based on the clock speed in the detection equipment, is compensated by adjusting the sampling rate.

Calibration

Prior to the actual PD data acquisition, the measuring system needs to be calibrated. This is done by injecting a pulse at on cable end, while measuring the resulting signal at the sensors at both cable ends. This is repeated with a pulse injected at the other cable end. Pulse injection in PDOL is done with the same equipment as used for the pulse based time synchronization, which is patented [3]. In this way, the transfer impedance for the PD pulses to both sensors can be derived. By repeating this calibration on a regular basis, the consequences of changes in the network connected to the cable under test, can be measured and the transfer impedance applied can be adjusted. During measuring period of weeks, months or years, changes can be caused by e.g. switching or connection of an additional power cable to one of the RMU-s. In fact this is on-line calibration. It can be repeated as often as needed. A calibration repetition rate of one per hour is foreseen to be adequate for most measuring situations and will therefore be incorporated in PDOL.

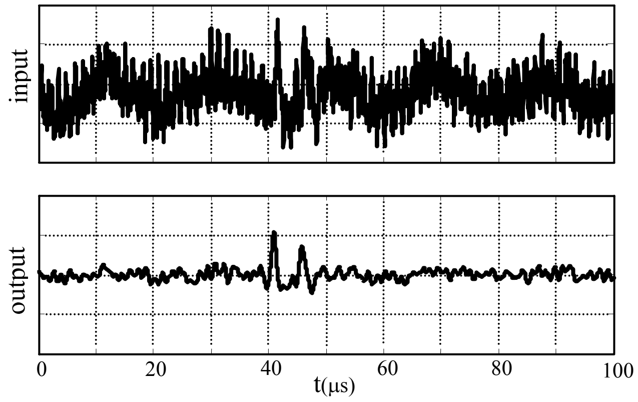

Figure 4 A noisy PD signal obtained in an on-line experiment and the signal after matched filtering.

Noise reduction

Practical PD measurements are impeded by noise and interference. In general, three main disturbance classes can be distinguished, namely radio broadcasts, broadband background noise, and finite-energy interference. After digitization of a data-block, radio stations can be suppressed using adaptive notch filters [8] or cancellers [9], which hardly affect PD signals. However, broadband noise poses a fundamental limit on PD detection. Matched filtering is a technique for detection of pulses in the presence of noise, which is optimal in the sense that the average signal to noise ratio (SNR) at the filter output is maximized (see figure 4). If the noise is white, the impulse response of the filter equals the time-reverse of the PD signal. Using PD signal models, filters are designed that are matched to the expected PD signals. The signal model incorporates all components present in the path between a possible defect and the digitizer, including the cable properties, sensor characteristics, etc. [6], [10]. In practice, the noise power distribution is frequency dependent, and components in the low MHz range dominate. Therefore the filters are automatically adjusted to the situation at hand, such that spectral regions with high SNR are amplified and regions with low SNR are suppressed.

In addition to its noise suppressing capabilities, a matched filter also provides a means to determine accurately some important PD parameters [10]. Since the charge of a PD pulse is unknown, the filter is matched to a scaled version of the actually measured pulse. Because of this linear relation, the PD charge can be determined directly from the maximum filter response. Moreover, a matched filter can be designed such that the maximum output occurs at the arrival time of the PD signal, and thus provides a basis for PD localization.

In order to achieve monitoring of PD activity, huge amounts of data have to be analyzed. Clearly, monitoring is practically feasible only if data processing can be fully automated. In the PDOL measuring system, the application of matched filters with appropriate maximum correlation detectors results in reliable analysis of on-line measurements with PDOL and automated detection of PD signals in the presence of high noise levels.

Proper filtering can mitigate the first two disturbance classes, however, a different approach is required for the third class. Finite-energy disturbances, such as thyristor pulses and PD pulses from equipment other than the cable under test, occur frequently in on-line PD measurements. Since signals are synchronously detected at both cable ends, pulses originating within and outside the cable can be distinguished by examining the difference in time of arrival. In addition, interferences can be discriminated based on signal direction of arrival. These are examples of very powerful tools applied in PDOL.

Data communication

PD data will be measured as often as needed, for instance once per 10 minutes. The measured PD data at each cable end is reduced to PD related data as much as possible. Typical PD characteristics, especially the shape of a pulse, are used to identify PD like signals. At both cable ends, this data is sent to a server. Data communication can be done by modem and telephone (a cell phone on remote locations), by LAN if available or other communication means. Such data transfer can be done on a regular basis, for instance once per 4 hours. However, the data transmission frequency to the server can be increased to e.g. once per 10 minutes in case of suspicious or even dangerous PD activity. Even higher measuring and data transmission rates can be obtained if needed, going to a kind of permanent monitoring.

The server combines the data obtained from the both cable ends to a PD map as shown in figure 5. It will be clear, that the PD data can be presented in many different ways, depending on the needs and customer wishes.

From the server, the PD maps can be sent via the web to all people that are interested, especially if specific predetermined warning levels are exceed.

FIRST MEASURING RESULTS

One of the first medium-voltage power cables diagnosed with PDOL is a 300 m long paper-insulated lead-sheathed cable (PILC) with a joint at position 96 m. This joint had a forced weakness, giving PD-s of several thousands of pC. But also the connected PILC cables have limited discharge activity. The result of 7 hours measuring time is presented in figure 5.

During the measurement, the PILC cable was on one side connected to an RMU with one additional power cable and a distribution transformer. The other end of the PILC cable was connected with an RMU that had only a distribution transformer. The measured PD-s, shown in figure 5, are expressed in discharge intensity. This is a way to incorporate both the cable length and measuring time. The discharge intensity is therefore expressed in nC per meter cable and per second measuring time (nC/sm).

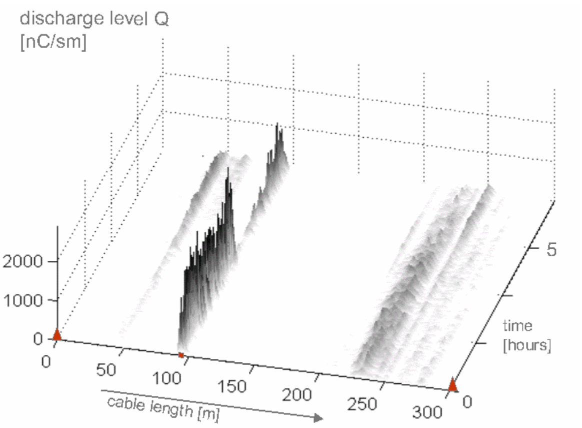

Figure 5 PD intensity in a PILC cable, measured with PDOL. The PD activity is expressed in nC per meter cable and per second. The PILC cable has a length of 300 m. There is a joint at 96 m. The total measuring time was 7 hours.

FUTURE ACTIVITIES

PDOL, as presented in this paper, is a measuring system that was made to show and prove its applicability. The components applied yet are not chosen to comply with mass-production. Moreover, a limited number of cables was tested so far. The activities foreseen in 2005 are directed to get a prototype of PDOL for further market evaluation, combined with extensive testing in the field.

On the longer term, on-line testing will at least partly replace the present off-line testing in open RMU-s (the meaning of an open RMU is explained earlier). The advantages make PDOL probably attractive in a much wider environment of cable diagnostics. Especially the facts that

1. a control room can monitor all cables connected to PDOL
2. not only long term defects, but also so called ‘short term’ defects can be traced prior to breakdown

are making PDOL a very powerful tool for power cable management. But effort is needed to develop new knowledge rules for the various cable components, as cable joints. Also it is interesting to learn whether water ingress via damaged lead sheaths of PILC cables can be detected in this way.

PDOL’s features look very promising, but the future will learn how far PDOL can support network owners indeed.

A few words about on-line PD detection with one sensor only. PD localization with one sensor is hardly possible. Nevertheless, such a system can be applied for warning, for instance if PD intensity of a whole cable system exceeds a specific level. Especially, EDF Energy in London is focusing on this way of diagnosing medium-voltage cables [11]. Their development team and the one from PDOL have close cooperation in a consortium directed to on-line PD monitoring in general. It is expected that this cooperation will be continued in the future.

ACKNOWLEDGEMENTS

This research work is supported by Dutch parties: Technology Foundations STW, applied science division of NWO and the technology program of the Ministry of Economic Affairs; Eindhoven University of Technology; KEMA Nederland B.V.; N.V. Continuon Netbeheer; ENECO Netbeheer.

REFERENCES

[1] E. Gulski et al. “*Experiences in partial discharge detection of distribution power cable systems*.” Elektra, June 2003. 35-43

[2] Dutch patent. “*Werkwijze en inrichting voor het opsporen en lokaliseren van onregelmatigheden in een diëlectricum”*. Patent nr. 1005349, 1998.

[3] Int. Patent. “*Method and system for transmitting an information signal over a power cable*”. Patent nr. WO 2004/013642.

[4] P.C.J.M. van der Wielen, J. Veen, P.A.A.F. Wouters and E.F. Steennis. “*Sensors for on-line PD detection in MV power cables and their locations in substations*”, Proc. of the 7th Int. Conf. on Properties and Applications of Dielectric Materials, 2003. 215-219.

[5] P.C.J.M. van der Wielen, J. Veen, P. Wagenaars and P.A.A.F. Wouters. “*Determination of substation model for correct interpretation of on-line measured PD signals from MV cable systems*”, Proc. of the 8th IEEE Int. Conf. on Solid Dielectrics, 2004. 747-750.

[6] P.C.J.M. van der Wielen. “*On-line detection and location of partial discharges in medium voltage power cables*”, PhD thesis, Eindhoven University of Technology, Eindhoven The Netherlands, 2005.

[7] E. F. Steennis et al. “*Partial discharge diagnostics of long and branched medium-voltage cables*”. Proc. of the IEEE 7th Int. Conf. on Solid Dielectrics ICSD 2001, 27-30.

[8] Z. Du and M. Mashikian. “*Self-learning digital filter for the field location of partial discharge in cables*”, Proc. of the IEEE ISEI, 1994. 245-248.

[9] J. Veen, P.C.J.M. van der Wielen, and E.F. Steennis. ”*Cancellation of continuous periodic interference for PD detection*”, Proc. of the IEEE ICSD, 2004. 707-710.

[10] J. Veen. “*On-line signal analysis of partial discharges in medium voltage power cables*”, PhD thesis, Eindhoven University of Technology, Eindhoven, the Netherlands, 2005.

[11] M. Mathieu. “*Moving towards a complete on-line condition monitoring solution*”. Proc. 17th Cired, Barcelona, May, 2003.