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Evaluation of different types of sensors and their positioning for on-line PD detection and localisation in distribution cables

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Abstract

Different types of sensors can be used for on-line detection and localisation of PDs in medium voltage cables. These sensors can be placed on different locations in the substations where the cable under test is terminated. Both aspects have a significant influence on the measured signals. In this paper both capacitive and inductive sensors are briefly evaluated, especially concerning their applicability for on-line measurements. Furthermore, when the sensors are applied on-line, it is essential to realize which signals are being measured. Especially when three-phase belted cables are being measured, the situation differs considerably from off-line situations. When the cable is on-line, i.e. powered by the network itself, all three the phases are energized simultaneously. This means the PD pulses are propagating through two distinctive propagation modes: the Phase-to-Phase (PP) mode and the Shield-to-Phase (SP) mode. In this paper the different possible locations in a substation for placing sensors are discussed, with respect to the measured propagation modes, signal- and interference sensitivity, safety and practical applicability. Field measurements confirm the findings.

Keywords: on-line, partial discharge, medium voltage cable, belted power cable, sensor, capacitive sensor, inductive sensor, propagation channels, sensor position, sensor location

1. Introduction

On-line partial discharge monitoring of medium and high voltage cables has a number of important advantages (e.g. [1]). Firstly, the data is continuously registered so temporal PD activity, or PDs occurring shortly before failure, are also captured, in contrast to occasional off-line tests. Secondly, installing the measuring system can, in principle, be done on-line without having to disrupt the power delivery. This, together with the fact that after installation on-line monitoring hardly requires any personnel effort, makes it relatively cheap to operate for utilities. Thirdly, the cable is tested under exact operating conditions, that includes over-voltages and load variations, which may be more convincing as being indicative for the actual cable condition. The design of an on-line system has a number of challenges to deal with. Since the cable is connected to the power grid, the amount of noise and interference is much larger than is the case for off-line measurements. So the requirements for signal processing are much higher. If

measurements. So the requirements for signal processing are much higher. If measuring set-ups are needed at both cable ends to include localisation of defects, extra requirements arise for communication and accurate synchronization [2].
Another challenge involves the coupling to the cable to extract the PD signals. This includes not only technical demands like sensitivity, bandwidth, etc. The PD sensor must be installed in existing networks, preferably during operation, and it may not result in a safety risk or an additional risk of failure of the power grid. The choice of the sensor type is crucial; the two main categories of sensors, capacitive and inductive sensors, have each their specific advantages and disadvantages for the intended application. In several countries belted cables are extensively used in medium voltage grids. The three-phase conductors with one common shield complicate the description of the travelling pulses (PDs) along the cable. The implications of the different propagation channels through the cable will be discussed, together with the possible sensor locations in subsequent section. Field experiments were done to confirm the findings.

2. Capacitive versus Inductive Sensors

Capacitive sensors suitable for PD measurements can be subdivided into three main categories:

1. High voltage capacitors, connected to a phase conductor of the cable. The measurement of PDs is performed over a resistive impedance in series with this capacitor, resulting in high-pass filtering. This method is successfully applied for conventional off-line PD measurements (e.g. [3]), but has two main disadvantages for on-line application. Firstly, the high-voltage capacitor can only be mounted when the cable is de-energized, thereby not allowing PD measurements without interrupting the power delivery. Secondly, high-voltage capacitors are often not very reliable on long term and can therefore become a cause of fault themselves when being applied for longer measuring times, as is one of the purposes for on-line monitoring.
2. Installing an electrode of some shape in the vicinity of a phase conductor, resulting in capacitive coupling to this conductor. The obtained capacitance, however, is now highly dependent on the installation details of the substation, cable termination and positioning of this electrode. Furthermore, the capacitance is relatively low.
3. In modern substations a capacitor is sometimes integrated in the switchgear to detect the power frequency voltage on each phase conductor. The use of this capacitor for measuring small signals like PDs is in practice hard, due to its small value (usually smaller than 100pF). Moreover, this method would not be very universal, since it depends on the presence of this particular type of switchgear.

So one can conclude that capacitive sensors have important (if not crucial) disadvantages if applied for on-line measurements.

Inductive sensors can be modelled as a transformer of which the primary coil is in the circuit to be measured and the secondary coil in the measuring circuit. A very applicable inductive measuring system is the Rogowski coil, clamped around the conductor to be measured. In this way, the primary side of the measuring transformer is the ("single winding") conductor itself, which therefore does not have to be disconnected. A Rogowski coil is a toroidal coil with N equally spaced turns, having a constant loop area A. The mutual inductance is approximately:

$$M = \frac{\mu_0 AN}{2\pi R} \tag{1}$$

R is the radius of the Rogowski coil. A nice property of a Rogowski coil is that, ideally, the output is independent on the location of the primary conductor within the coil and external (homogeneous) magnetic fields. Usually for PD measurements air coils are not sufficiently sensitive. The mutual inductance can be increased by using ferro-magnetic material with high permeability μ_r (up to 10^5). If such core materials are used extra requirements arise. The material should not saturate, in particular not for the power frequency current. Depending on the location of the probe, the power frequency current can reach several hundreds amperes. To avoid saturation the flux density B in the material should be controlled. This can be done by implementing an air slit of a defined size d in the core. If $\mu_r >> 2\pi R/d$, the magnetic field inside this air slit is dominant and the mutual inductance becomes:

$$M = \frac{\mu_0 AN}{d} \tag{2}$$

The air slit must be precisely controlled, since it determines the mutual inductance, which is increased with a factor $2\pi R/d$ compared to an air coil with similar size. Since the probe must be installed online, it should be possible to clamp it around a conductor. The clamping mechanism usually coincides with the slit position.

To summarize, toroidal sensors have some important advantages:

- Since toroidal coils result in measuring the total enclosed current, this method is less dependent on the geometry of the substation.
- There is no galvanic contact with a conductor required; therefore the sensor can often be mounted safely without interrupting the power delivery and can never become a cause of faults on the power grid itself.

Since these advantages are essential for on-line PD measurements, we will focus on the application of inductive sensors. The challenge for on-line PD measurements is to find the optimal locations for these sensors with respect to their sensitivity, interference level, signal distinction and universal applicability.

3. Sensor Locations

In Figure 1 a simple representation of a cable termination as a lumped component is shown. The load in the substation is denoted as impedance Z_L. As is indicated, two main current circuits can be defined. The differential mode (DM) current, which is flowing through the inside cable structure (phase conductor(s) and shield) and the cable load impedance at the termination. This current includes the PD signal we want to measure. The DM circuit along the cable is well shielded, so noise and interference mainly originates from the connected power grid. The common mode (CM) current flows through the shield of the cable and back via several other earth paths, which in practice are always present. This circuit is actually a large antenna for noise and disturbance and does not contribute to PD signal detection.

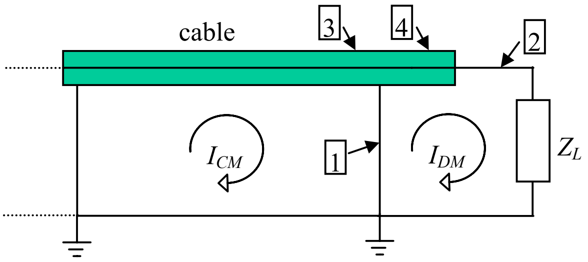

Figure 1. Simplified representation of a cable termination in a substation. The two main current circuits DM and CM are indicated, the numbers indicate sensor locations discussed in the text.

Various locations for current sensor installation are indicated in Figure 1.

1. Position 1 is the earth connection of the cable on which a current sensor can be installed without safety hazards. As can be seen in Figure 1, both the DM and CM currents will be measured; therefore, the DM current is unnecessarily disturbed. Moreover, if the sensor is installed further away from the cable termination, the earth connection is branched and PD detection becomes hardly possible.
2. At position 2, the other side of the load impedance, the DM current could in theory be measured separately. However, the sensor should be clamped around the energized phase conductors, which obviously poses a safety hazard and is also usually difficult due to the dimensions of the cable termination. In modern switchgear the phase conductors inside the termination even cannot be reached. This method can only be applied if the sensor is integrated in the cable termination (such as done in EHV cable accessories, e.g. [4]).
3. At position 3 a current probe can be installed quite easily and safely. The enclosed current, however, includes both DM and CM currents flowing through the shield and the DM current flowing (back) through the phase conductors of the cable, resulting in a net signal equal to the CM current, with no PD signal.
4. Position 4, around the cable shield before the actual cable termination, past the last earth connection of the cable. A current probe can be installed safely here, and only the DM current is measured.

Apparently, position 4 is a good location for PD current measurement. In the case the construction of the cable termination does not allow the placement of the sensor there, one can use position 3, but the last earth connection has to be re-allocated back through the current probe. The CM current is then subtracted from the total signal and only the DM current remains.

4. Pulse Propagation through Three-Phase Belted Cables

In belted cables, the distribution of the currents induced in the conductors (3 phases and shield) at the PD site depends on the position of the PD within the dielectrics and its direction, [5]. Next the induced currents propagate through the belted cable, which can be modelled as a multi-conductor transmission line. In e.g. [6] it is shown, that a rotational symmetric three-phase cable has two distinct propagation channels: the Shield-to-Phase (SP) channel, the sum current through the three phase conductors (returning through the shield) and the Phase-to-Phase (PP) channel, the difference between two phase currents (with zero current in the third phase). The cross talk between the two propagation channels is very small [6], so the distribution of the induced currents over the different conductors upon a PD determines from which channel the signals can best be measured. Therefore, it is useful to subdivide sensor locations into two main groups: sensors detecting signals from the SP channel and those detecting from the PP channel.

Sensors around the cable earth connection, which detect signal from the SP channel, are already successfully applied [7], however, sensors detecting signals in the PP channels have some important advantages:

- The PP propagation characteristics are better, i.e. less attenuation compared to the SP channel, e.g. [6].
- The signal propagation path through the substation is usually better defined, because of the equally shaped and more or less parallel routed conductors and rails (compared to the virtually arbitrary shape and routing of the earth connections).
- By detecting in the PP channel, a differential measuring method is implicitly applied, thus cancelling most of the noise and interference that is present due to radiation, since these disturbing signals almost equally couple to the phases. Moreover, since the earth connections in the substations form all kinds of antennas, due to their geometric arrangements, the noise and interference contribution of these conductors is much higher than of the phase-conductor connections and rails.
- The phase terminations and rails are of a more standardized shape and equivalent for similar substations. Therefore the variety of sensors, which are adapted to fit on specific configurations, can be smaller.

Consider the (practical) situation that three sensors measure the signal between each phase conductor and the earth connection separately. In this case both SP and PP channels can be calculated by respectively adding and subtracting the relevant phase currents (or voltages in the case of capacitive sensors). On one hand, application of more sensors implies more effort and more expensive equipment. On the other hand, the extra information can give an indication of the position of the PD in the cross-section of the cable at the PD site [5]. This extra information is useful to determine the nature of the defect causing the PDs and can therefore help to evaluate its potential danger.

In the discussion in section 3, sensor location 2 in Figure 1 was considered unpractical. In many MV substations, however, a transformer is connected to the MV cable with three separate single-phase cables (usually with a length of about 4 meters). Their shields are earthed, usually at one side, allowing installation of sensors around these cables while they are energized. Consequently, each sensor measures the current through an individual phase, which allows distinguishing between both the SP and PP channel currents. This option comprises all advantages mentioned before. The one sided grounding of the cables connecting the distribution transformer allows yet another option for sensor installation. Since such cables have a capacitance in the order of 1 nF, the current flowing through the earth connection of this cable is coupled to the voltage of this cable by its capacitance. Measuring this current is therefore capacitive measuring of the voltage change e.g. due to a passing PD signal.

5. Measurements

A series of measurements have been performed on cables in several 10 kV substations in order to determine the noise and interference level. Sixteen 10 kV cables from different utilities in the Netherlands have been measured on both sides. The first 2 graphs in Figure 2 show a PSDF (Power Spectral Density Function) obtained from a series of noise measurements in both the DM and CM circuits of the SP channel of one cable.

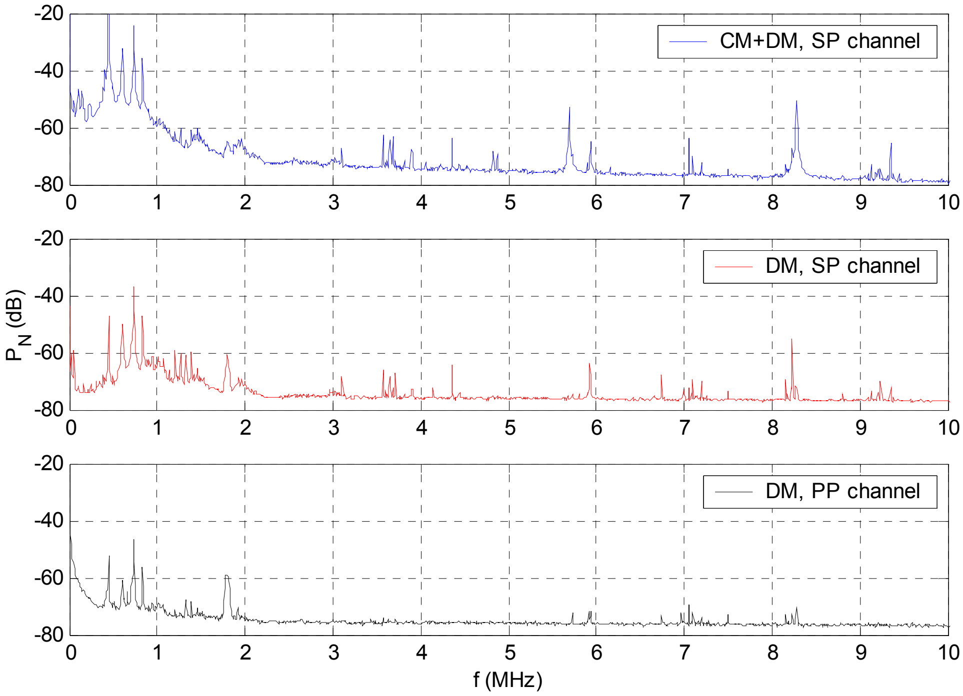

Figure 2. PSDF of noise signals measured in the CM and DM circuits and the DM circuit of the PP channel.

As can be clearly seen, the graph of the CM circuit shows much more and higher noise peaks in the low MHz range. Although the precise PSDF differs slightly from substation to substation, all measurements show that the CM circuit contains a relatively high noise level compared to the DM circuit. The third graph in Figure 2 shows the PSDF of the noise in the PP channel of the same cable. This latter location confirms the earlier assumption, that this PP channel will give the best SNR.

Figure 3 shows a small signal in a noisy environment, measured at the three places corresponding to Figure 2.

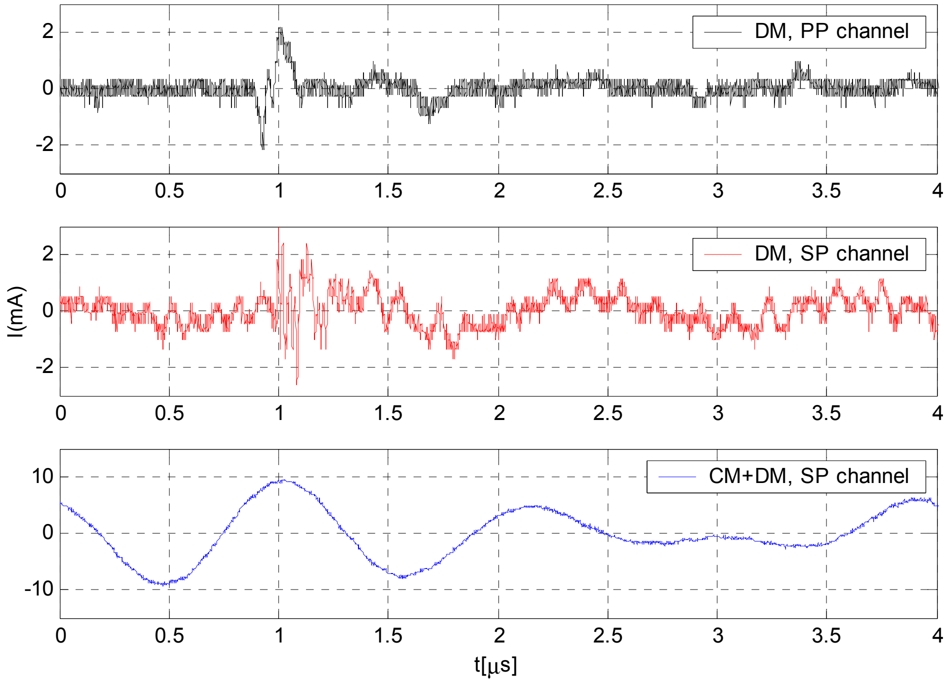

Figure 3. PD signals in both the PP and SP channels and in the CM+DM circuit.

These ‘raw’ signals, i.e. without any filtering point out the difference in SNR in both channels. As expected, the PP channel shows the best SNR. Usually, if also the CM current is measured (position 1 in Figure 1), no PD can be recognized without filtering, as is shown in the third graph of Figure 3.

6. Discussion

One important aspect not extensively discussed in this paper is the substation impedance. For both capacitive and inductive measurements it is essential that the termination load is known. The pulse travelling through the cable experiences an impedance change at the cable termination from the characteristic cable impedance to the load impedance. If only wavelengths much larger than the dimensions of the substation conductor lengths (usually smaller than 10 m) are considered, the substation impedance can be regarded as a lumped load impedance. The detection bandwidth for cable diagnostics is limited by high-frequency attenuation of the signals, usually to the low MHz range, corresponding to ca. 100 m wavelength. Therefore, in most cases, the condition for the lumped circuit assumption of the substation is satisfied. Another aspect of the substation impedance is how connected equipment contributes to this impedance. The impedance can mainly be constructed from the parallel-connected outgoing cables and the transformer, including its connecting cables. In order to calibrate the actual sensor sensitivity, the value of the impedance over which is being measured must obviously be known. The leaving cables can be modelled as parallel characteristic impedances. The transformer typically behaves as a capacitance in the frequency range of interest, as is shown in [8]. For operating an intelligent PD detection and localisation system, either this information should be available beforehand, or should be obtained on-line. The latter option is preferred, since the actual behaviour of a substation in this frequency range may change e.g. due to maintenance or reconfiguration of the grid.

7. Conclusions

When doing on-line measurements, inductive measuring is in most cases preferred. Two positions show to give the best results since these give the best SNR: (*i*) clamped around the cable shield past the last earth connection for measuring SP currents and (*ii*) around the shielded transformer cables (or their earth connections) for measuring all phases separately, and thereby determining both the PP and SP channel signals. The latter possibility even makes it possible to use both inductive and capacitive measuring techniques simultaneously. The sign of the voltage and the current results in the direction of the Pointing vector, and therefore gives the travelling direction of the measured signal. This enables us to distinguish between signals coming from the cable under examination (PDs) and signals originating from the other side (noise and PDs from other cables).

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