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Multiple Task Sensors/Actuators for On-line PD Diagnostics on MV cables

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Abstract
On-line Partial Discharge (PD) detection and fault location in Medium Voltage (MV) cables requires multi-purpose sensors. Besides PD detection itself, tasks as time-base alignment and signal calibration must be implemented if a two-sided measurement topology is applied. The option of inductive pulse injection has proven to be a powerful tool for synchronisation and for calibrating the effect of substation impedances on PD signals. Coils needed for pulse injection/detection and for the actual PD detection can be shared, since the optimal bandwidths are similar. Two-sided measurement also requires a communication channel. The maximum carrier frequency for general Power Line Communication (PLC) allowed by standards is far below the frequency range suitable for PD diagnostics. This paper discusses concepts to integrate all tasks, including PLC for PD data, with a minimal number of coils needed.

1. Introduction
Partial discharge detection and location is one of the available techniques to diagnose MV power cables. Usually, the cable is temporally disconnected, and externally energised (Fig. 1, off-line). The PD events result in pulses travelling in both directions along the cable. Since the far cable end is open, full signal reflection takes place and the origin of the PD can be established by means of Time Domain Reflectometry (TDR). The development of an on-line technique is motivated by the following advantages (Fig. 1, on-line) [1,2]: switching of cables can be omitted, no external power source needed, and continuous monitoring allows detection of trends in PD behaviour. However, no clear signal reflection is guaranteed, since substation impedances now load the far end of the cable. Two-sided detection can be used instead of TDR, but this solution results in a few complications. Location of PDs requires accurate timing. Therefore, the time bases at both cable ends must be aligned. Further, galvanic contact with the MV should be omitted to prevent any operational hazard. PD signals are preferably detected by means of coils around grounded conductors in the substation. The impedances of substation equipment are part of the detection circuit, since they effectively close the current path for the PD signals. Their effect on signal waveform and amplitude must therefore be calibrated. Recent work proved the feasibility of pulse injection, both for synchronisation and calibration [3,4]. The data gathered at both cable ends must be linked. An on-line PD detection and location system therefore should preferably include a communication channel. At present, substations are generally not equipped with provisions for communication. In this paper, the grid itself is considered as a communication channel. The main obstacle for applying PLC to MV cables is related to signal coupling into the grid [5].

In section 2, aspects concerning the pulse injection system used for synchronisation and substation characterisation, and to be used for PLC are discussed. Section 3 is directed to difficulties when the communication method has to comply with standards [6,7]. Alternative communication methods taking advantage of the already present pulse injection system are discussed in section 4. In section 5, a concept for integrating all required tasks is proposed.

2. Pulse injection
2.1. Half cycle LC-oscillation
A time resolution for synchronisation of at least 100 ns is required for fault localisation within 10 m [1-3]. To obtain this resolution, pulses serving as time stamps are injected at one side of the cable. The optimal pulse bandwidth is basically a compromise between high time resolution and good signal propagation through the power cable. An appropriate pulse can be generated by means of the circuit depicted in Fig. 2. A capacitor \( C_0 \) is discharged over the self-induction \( L \) of the injection circuit.
coil, via a tuned capacitor $C$ to obtain the desired pulse width. A (MOSFET) switch in the circuit blocks the resulting oscillation after a half cycle. A typical waveform is shown in Fig. 2 (bottom). This primary excitation current $I_0$, applied to a coil clamped around a substation conductor, results in a known induced voltage $V_{sec}$ over the impedances present in the secondary substation circuit according to:

$$V_{sec}(\omega) = j\omega M I_0(\omega)$$

This voltage will induce a current $I_{sec}$ in the circuit, which is made up by the cable under test $Z_c$ and the impedance of all substation equipment closing the circuit. The latter impedance may consist of a distribution transformer or other power cables. Also the circuit inductance and the capacitance of the cable connecting the transformer have to be included [4].

![Fig. 2 - Basic circuit for pulse injection (top). The lower circuit generates a current $I_0$ (see waveform), by discharging a capacitor over the injection coil. The upper circuit, formed by the substation, is coupled via mutual inductance $M$ and the cable propagation characteristics [4,8,9]. In frequency domain, the waveform at the injection side depends on the injection current and lumped substation impedances $Z$, according (Fig. 2):

$$I_{sec}(\omega) = \frac{j\omega M}{Z_c + \left(\sum 1/Z_c(\omega)\right)^{-1}} I_0(\omega)$$

$Z_c$ represents the impedance of the cable containing the injection coil; the sum in the denominator includes all impedances closing the current path. The overall substation impedance can be determined from the known injection waveform, injection coil characteristics and the secondary current measured with the PD detection coil. The sensor at the cable far end detects the waveform after propagation along the cable connection. It implicitly contains information on the signal propagation characteristics. In [1,2] it is shown, that by applying pulse injection and detection at both cable ends the channel can be fully characterised.

### 2.3. On-line measurements

As an example for pulse injection in a life circuit an 866 m cable, terminated by two small substations, was investigated. Both substations contain a distribution transformer. One substation included two additional cables. For injection, a Rogowski coil with a mutual inductance of $M = 42$ nH was mounted around the earth screen (beyond the last earth connection as illustrated in Fig. 3). Pulses are either injected in the right or the left cable end. In both cases the secondary current is measured over the same cable screen as injection takes place by means of commercial current probes (sensitivity 1 V/A). The characteristic impedances of the two extra cables, and the distribution transformer impedance close the injection circuit in the substation at the right side. For injection in the left substation only the transformer closes the current path. In [5] it was shown that in first order approximation a distribution transformer can be modelled by primarily a capacitive behaviour. The fits in Fig. 3 were obtained by choosing characteristic cable impedances of 12 $\Omega$, and a total value of 3 nF for the transformer (1 nF) together with its connecting cables (2 nF) as dominant impedances. Besides the circuit self-inductance, additional circuit resistance (skin effect and radiation losses) was introduced in order to get good agreement. In principle, using the acquired values for the substation impedances, the cable propagation characteristics can also be determined when the signal at the far end is measured.

![Fig. 3 - Response on injected pulses, measured at two substations connected by a PILC cable, including the calculated waveform (thin line) at the injection side. Top figures: injection cable loaded with distribution transformer (Tr.) and two additional cables; Bottom figures: injection cable only loaded with distribution transformer.](image-url)
3. Power line communication

The cable is in normal operation during on-line diagnostics, and therefore PLC should comply with regulations. In usual PLC applications the final goal is to transfer information to residents, meaning that part of the communication takes place over the low-voltage grid. In most European countries the communication method has to meet the CENELEC EN50065 standard [6]. However, this standard regulates PLC on the LV grid. For signalling on MV electrical installations the standard IEC 61334-3-1 [7] applies, and frequencies up to 500 kHz can be used. In this section the implications of the standards are discussed.

3.1. Coupling efficiency

In an earlier study the feasibility of inductive coupling for PLC was investigated. A 4 km three-phase belted PILC cable was loaded (off-line) on both sides with several impedances, resistive as well as capacitive [5]. Load impedances of 10 Ω and 100 Ω covering the range of actual cable characteristic impedances, 1 nF and 10 nF representing transformers (including extra capacitance from connecting cables) were chosen as being indicative for the performance of the communication channel. The transfer functions shown in Fig. 4 relate the injection coil excitation current $I_0$ to the resulting current $I_{out}$ at the other cable end. Signal coupling was accomplished by means of air coils (Rogowski) with a mutual inductance $M$ of 1.86 μH. The transfer function for a not characteristically terminated cable with length $\ell$ and characteristic impedance $Z_c$ is given by [5,8]

$$H(\omega) = \frac{I_{out}}{I_0} = \frac{1}{\sqrt{2}} \frac{\alpha M}{Z_c} \tau_\ell(\omega) \cdot \tau_r(\omega) e^{-\gamma l(\omega)} \cdot \frac{1 - \rho_\ell(\omega) \rho_r(\omega) e^{-2\gamma l(\omega)} - 2\tau_\ell(\omega)}{1 - \rho_\ell(\omega) \rho_r(\omega) e^{-2\gamma l(\omega)}}$$

with $\tau$ and $\rho$ the current transmission and reflection coefficients at the cable to substation transitions at both cable ends (index $r,t$). The denominator in the right hand factor is approximately one, because of signal attenuation over 4 km, resulting in:

$$[H(\omega)] = \frac{\alpha M}{2Z_c} \tau_r(\omega) \cdot \tau_\ell(\omega) e^{-\gamma l(\omega)} \cdot \tau_\ell(\omega) = \frac{2Z_c}{Z_c + Z_{in}(\omega)}$$

The frequencies chosen for the measured values, indicated with symbols in Fig. 4, comply with the EN50065 standard (< 95 kHz for utilities). This data serves as calibration for the calculated curves, which are extrapolated up to 1 MHz. These curves are based on two fit parameters: cable impedance $Z_c = 13$ Ω (about 40 Ω for each parallel phase), and attenuation coefficient due to skin effect $\alpha(\omega) = 2.5 \times 10^7 \sqrt{\omega} \text{m}^{-1}$ (ω in s⁻¹). The large range in transfer function magnitude indicates the high sensitivity of the system performance both with substation configuration and frequency. It should be noted, that a transformer will not behave as a perfect capacitor up to frequencies relevant for PD detection (several MHz), but will exhibit resonances. An obvious resonance occurs owing to its capacitive behaviour together with the self-inductance of the connections (several hundreds nH). The bold line indicates the sensitivity of an available test FSK-based communication device. It is seen that under unfavourable conditions, both substations containing only a distribution transformer, the sensitivity is insufficient. Frequencies up to 500 kHz, as allowed by IEC 61334-3-1, will improve the injection efficiency. Consider the situation of a power cable only loaded with a distribution transformer. The induced voltage over the substation circuit is proportional to frequency. Moreover, the impedance closing the injection circuit is the transformer with its connecting cable, which are expected to behave dominantly capacitive. This means that the secondary current is proportional to the square of frequency, and consequently the injected power proportional to the fourth power. As can be observed from Fig. 4, signal attenuation from cable propagation characteristics still only has minor influence at 500 kHz. In addition, at the detection side signals are more efficiently extracted at higher frequency as well.

![Fig. 4 - Extrapolation up to 1 MHz of the transfer functions (lines) based on experimentally determined values (symbols) within the CENELEC A-band, available for utilities. The bold horizontal line element indicates the sensitivity of a FSK-based test device.](image-url)

3.2. Implications of standards

Since the expected data rate required for the present purpose is low, the maximum allowed carrier frequency does not pose a real restriction for PLC. Problems arise only from the inductive coupling efficiency to the 10 kV grid. The option investigated in this paper is the feasibility of the pulse injection system already applied for PD-online diagnostics. As discussed in section 2.1, the signal is basically a differentiated cosine (owing to the inductive coupling) with amplitude $I_{max}$, which is terminated after a half cycle (total duration $T/2$):
\[
I_{\text{inj}}(t) = \frac{M}{Z_c} \cdot \frac{d}{dt} I_{\text{max}} \sin(2\pi f T_0); \quad T_0 \leq t \leq T_0 / 4
\]

It is assumed that the main impedance in the substation circuit is the impedance of the cable under test itself. This situation can be regarded as a scenario where maximum power is injected into the cable. The frequency spectrum of the injected current is given by:

\[
I_{\text{inj}}(f) = I_{\text{max}} \cdot \frac{2M}{Z_c} \left(1 - (fT_0)^2\right)^{1/2} \cos\left(\frac{\pi f T_0}{2}\right)
\]

The power spectrum of a measured signal in the cable upon a coil excitation pulse, similar to the pulse shown in Fig. 2, is given in Fig. 5 as a function of the product \(fT_0\). Since the excitation pulse waveform differs from a perfect cosine shape, the dashed line calculated for the spectrum envelope deviates. The resulting broadband spectrum has a maximum at about \(f = 1/T_0\), i.e. 500 kHz for 1 \(\mu\)s pulse duration. The IEC standard limits the allowed spurious emission outside the bandwidth down to 10 \(\mu\)W measured with a bandwidth of 300 Hz. As with a (quasi) periodic data signal the power spectrum is discrete. These peaks can be spread over a wider range if not fixed time intervals for logic “0” and “1” are applied, but if both intervals are modulated such, that the averaged spectrum becomes more or less continuous. The reason for having this IEC standard is basically to prevent signal coupling to the low-voltage side or to the high-voltage at the transmission level. MV signalling may interfere with PLC systems operating at the other levels. However, high-frequency signal coupling between primary and secondary coils of power transformers hardly occurs, and no problems are expected from interference. As a matter of fact, if such coupling would occur, PD detection at the low-voltage side would even have been an option.

**4. Integrating PLC with pulse injection**

We pursue communication methods by applying pulses of constant shape, generated as described in section 2. Modulation of the pulses can be realised via time differences between successive peaks, amplitude of the peaks or a combination of both. The latter situation resembles methods applied in computer modems, where phase-shift and amplitude keying are combined. As modulation techniques are not part of our expertise, only modulation with two distinct time intervals is considered here.

The pulses as they enter the power cable are distorted. Especially when the substation at the end of the grid consists of only a distribution transformer, ringing tends to occur for several microseconds (Fig. 3). Half duplex communication is relatively easy to implement, since only one side is sending at a time. For more flexible interfacing with standard communication protocols full duplex is preferred. At either side, injected and detected pulses must be clearly distinguishable, since ringing from pulse injection hampers detection of signals from the other end, which may have much lower amplitude. This reduces the maximum pulse repetition rate further. Assuming a minimum pulse separation time of ten times the frequency of the half-cosine pulse, results in approximately 50 kHz repetition rate. This still allows for sufficient data transfer for the intended purpose.

Fig. 6 - Pulse sequences for bi-directional communication by pulse injection. Pulse separation (equal intervals or shifted for every second peak) defines the logic state. Sequences a and b are the signals at the far end, if the response there is halfway between the received signal. Sequences c and d are obtained assuming a propagation delay resulting in overlap (indicated with ellipse) between sent and received pulses. Applying a time shift backwards (arrow) in sequence e with respect to b, prevents coinciding signals in sequences f and c. The dark triangles indicate the duration of possible ringing.

A possible pulse sequence scheme for full duplex communication is depicted in Fig. 6. As a simple modulation example a 50 kHz repetition rate with 1 \(\mu\)s pulses is taken. The pulses are equally spaced for e.g. logic level “0” (solid line), and for a “1” every other pulse is shifted in time with e.g. 10% of the average pulse repetition rate. Sequence a shows the signals received at the far end for communication initiated at the near end. The far end responds by putting its pulses halfway in between (sequence b). The “triangles” behind each pulse indicates the time during which
ranging may occur. If signal propagation delay is neglected, the signals at the near end are separated in time as well. However, propagation time forth and back a long cable takes up to several microseconds. This is illustrated by the pulse sequences $c$ and $d$ for respectively the injected and detected signals at the near end. The pulses overlap in the particular situation shown. The sequence returned by the far end can be shifted backwards such, that no interference occurs with the received signals (compare sequence $e$ and $a$), and at the same time the signals at the near end become separated (compare sequence $f$ and $c$).

The proposed method requires a priori information on the channel delay. For the present application this information must be available anyhow, since accurate PD location depends on precise knowledge of the cable propagation delay. To obtain this information, a “system identification” phase, which runs before the actual PD measurement, has been defined in the software controlling the PD-Online system [1,2]. In this phase pulses are sent in both directions through the cable in order to determine all relevant parameters, amongst others the channel delay. However, to construct the channel model, communication is already required in this phase. A possible solution is to communicate the limited amount of system characterisation data at a rate, low enough to neglect the channel delay. Next, from the obtained cable model, the time shift required to prevent pulse overlap at either cable end is calculated. In fact, information on pulse shape and noise level is obtained as well. The communication channel behaviour becomes fully predictable and an optimal communication strategy can be evaluated. This may also include reduction of the injected pulse power to prevent any risk of violating electromagnetic compatibility.

5. Conclusion

If the method proposed in the previous section is applied for communication, the bandwidth of the PLC coupling coils is close to the optimal bandwidth needed for PD detection, time synchronisation and system characterisation. As inductive coupling is reciprocal, this opens the opportunity to combine all tasks within a limited number of coils. The minimum number of coils needed at each side is two, since substation characterisation requires injection of an calibration pulse and simultaneous detection of the resulting current in the substation circuit. Optimal position of sensors is discussed elsewhere [1,2,4,9] including options for an additional sensor to determine the signal propagation direction. Here, only a possible subdivision of tasks for a set of two coils is given.

PD-detection: This is the main objective of the diagnostics. The PD signal must be obtained as sensitive as possible with sufficient bandwidth and without unnecessary signal distortion. Commercial sensors with ferromagnetic core are available with a bandwidth of several hundreds of MHz.

Substation characterisation: Sufficient signal magnitude in the low MHz range can be realised with an air coil (Rogowski). The ferromagnetic sensor at the injection side can detect the resulting substation current. At the cable far end the signal is detected as well in order to extract the cable propagation characteristics. Synchronisation: Also synchronisation requires injection of pulses (at one end) and detection of pulses (at the other end). The coil requirements are therefore similar as for substation characterisation. Communication: Detection for PLC involves a demodulation circuit, which loads the sensor and may disturb the detected signal. Therefore, the Rogowski coil is applied for both transmission and reception.

6. References


