A New Procedure for Partial Discharge Localization in Gas-Insulated Switchgears in Frequency Domain

Stefan M. Hoek[1*], Uwe Riechert[2], Thomas Strehl[3], Stefan Tenbohlen[1] and Kurt Feser[1]
[1]University of Stuttgart, IEH, Pfaffenwaldring 47, 70569 Stuttgart, Germany
[2]ABB Switzerland Ltd - Gas Insulated Switch Systems, Zürich, Switzerland
[3]LEMKE DIAGNOSTICS GmbH in Volkersdorf / Dresden, Germany
[*]E-Mail: Stefan.Hoek@ieh.uni-stuttgart.de

Abstract: This new method will permit a cost-efficient localisation of partial discharges (PD) in gas-insulated switchgears (GIS). It uses the interference phenomenon of two superimposed sensor signals. The signal interference results in the time delay (Δt) between the two signals. Evaluating this time delay a localization is possible. Two related sensor signals are required to receive acceptable results for the measurement procedure. Considering the dispersion effects of higher modes in GIS only a certain frequency range is useful for the measurement. The interferences can be measured at various setups.

INTRODUCTION

The liberalization of the energy market forces utilities to reduce costs. A condition based, effective and fast maintenance strategy is essential. Considering the maintenance strategy of GIS, a sensitive PD detection is essential to detect defects. The type of the PD defect can be recognized with different proved methods like pattern recognition with the phased resolved partial discharge (PRPD) analyses or other techniques. To assess the risk of a defect, its location is additionally important. Thus, a sensitive PD detection with estimation of the nature of the defect and a fast and exact locating is advantageous. Hence the demand for reliable and economic measurement tools to locate PD-sources is still increasing.

PD LOCATING IN GIS

Several methods can be used, based on different physical phenomena. Methods based on a time delay evaluation between different propagating modes [1] and directional couplers [2], have shown to be unpractical [3]. The most practical methods are based on sectionizing, electrical time-of-flight measurements, acoustic measurement and a combination of all of them. Another newly investigated method, presented in this paper, uses the interference measurement in the frequency domain. Measurements in frequency domain features various advantages like less hardware effort compared to conventional methods in time domain.

Locating in time domain

Very fast electric pulses with rise times below 1 ns, emitted by a PD source, propagate in all directions along the GIS duct. A simple and obvious way of locating is the measurement with the time-of-flight method. By the time-of-flight technique the time difference between the wave fronts arriving at two UHF- PD - sensor indicate the location of the PD source. The time difference (Δt) is usually in tens of 1 ns, so that a fast digital acquisition has to be applied for measurements [3].

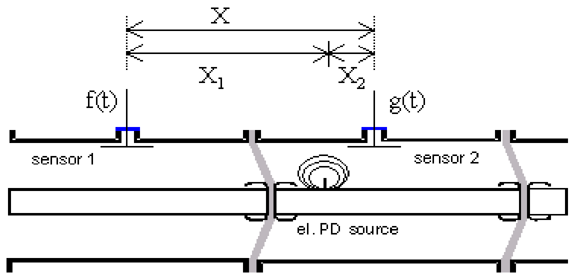

Fig. 1: Cross section of a GIS

The distance X_1 can be calculated with the equation (1) in case the time difference (Δt) is known. X represents the distance between the sensors and c_0 is the propagation speed of the wave in the GIS ($c_0 = 0.3$ m/ns) [3].

$$X_1 = \frac{X - (X_2 - X_1)}{2} = \frac{X - c_0 \cdot \Delta t}{2} \qquad (1)$$

The time difference is determined by the initial impulse steepness of the two signals. If the initial start of the signal is not totally clear or there are different signal-to-noise ratios (SNR) of the two signals, the measurement of the time difference Δt is not easy detectable in all cases.

Interference measurement

Another method to localize PD in GIS is to use the frequency domain. The interference phenomena of two sensor signals, which are added, should give information about the time delay (Δt) between the signals. A measurement procedure with a spectrum analyser instead of a cost-intensive fast digital oscilloscope, would be more economical.

The idea is based on the displacement law of a Fourier-Transformation of the received signals.

$$FFT[f(t-\Delta t)] = FFT[f(t)] \cdot e^{-j\omega\Delta t} \quad (2)$$

Measurement procedure To visualise the interference phenomena it is insufficient to make only one measurement. There are three power spectrums needed, which are compared in a characteristic way. The power spectrum is the absolute value of the complex FFT. The three power spectrums are obtained from Sensor 1 (3), Sensor 2 (4) and the added signal of Sensor 1 and 2 (5) with a conventional spectrum analyser. The last signal is obtained with a RF power splitter, with no further reflections or other disturbing influences (Fig. 10).

$$F(\omega) = \left| FFT[f(t)] \right| \quad (3)$$

$$G(\omega) = \left| FFT[g(t)] \right| \quad (4)$$

$$H(\omega) = \left| FFT[g(t) + f(t-\Delta t)] \right| \quad (5)$$

These three resulting signals are combined in (6). So the time difference (Δt) will be estimable with the resulting cosine function in case of f(t) = g(t).

$$\frac{H(\omega)}{F(\omega)+G(\omega)} = \left| \cos\left(\frac{\omega \cdot \Delta t}{2}\right) \right| \quad (6)$$

This cosine function has equidistant minima (see Fig. 2) which can be interpreted as interference phenomena [4].

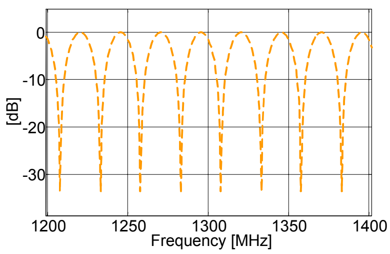

Fig. 2: Resulting cosine function from (6) for a Δt = 40 ns

Requirements Two related signals are required to obtain useful results from equation (6). Unfortunately this represents not a normal case in GIS. Current studies show that an magnitude difference is not critical if the nature of both signals is similar. For different magnitudes, the combined function (6) changes to the absolute value of a cosine function with decreased magnitude and an offset. To keep the characteristics of both signals similar the effect of dispersion should be kept as small as possible.

Three different types of wave modes which propagate in the GIS are distinguished. The TM_{mn}-mode ($H_z = 0$), the TE_{mn}-mode ($E_z = 0$) and the TEM-mode ($H_z = 0$, $E_z = 0$) (m and n mark the different types of wave modes). Every wave mode, except the TEM-mode, has its own critical frequency (f_c). Higher modes are able to propagate at frequencies above their own critical frequency (f_c). TEM-modes have no critical frequency and will propagate starting from 0 Hz. The critical frequencies depends on the geometry of the GIS. With an increasing cross section of the GIS, the critical frequency is decreasing. In Fig. 3 the critical frequencies of the first wave modes are shown for three different types of GIS [5].

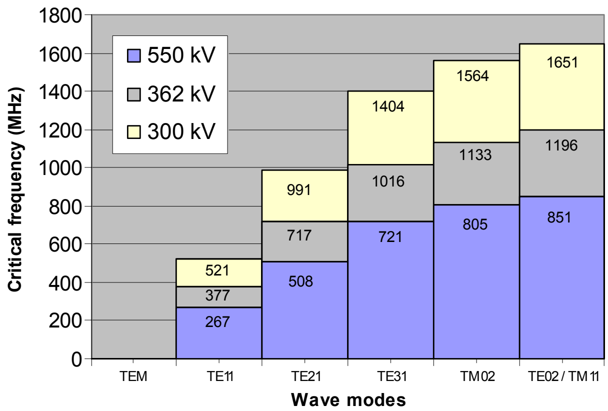

Fig. 3: Critical frequencies (f_c) within an GIS for 300 kV, 362 kV and 550 kV

The group velocity (v_g) of the TE- / TM-wave modes is frequency dependent which is a precondition for dispersion. The speed of the higher wave modes can be calculated according to the following equation [6].

$$v_g(f) = c_0 \cdot \sqrt{1 - \frac{f_c}{f}} \quad (7)$$

Below the lowest critical frequency of all modes (in GIS the f_c of TE_{11}), only TEM-modes are able to propagate. In this frequency range less dispersion effects exists and the interferences can be recognized. To measure in the frequency range below the first critical frequency, a low pass filter is applied, because the signal energy in the higher modes is much higher than in the TEM-mode (Fig. 10). One Requirement for a successful measurement is a sensitive measurement in this frequency range. All other effects influencing the signal within the GIS should be eliminated.

Measurement example The following measurement shows the method with a simplified setup. A pulse generator excites the signal in two cables with different length to generate the time difference (Δt). An attenuator reduces the magnitude of one signal.

For a better understanding the time-domain measurement is also visualized. They are in general not necessary for the procedure.

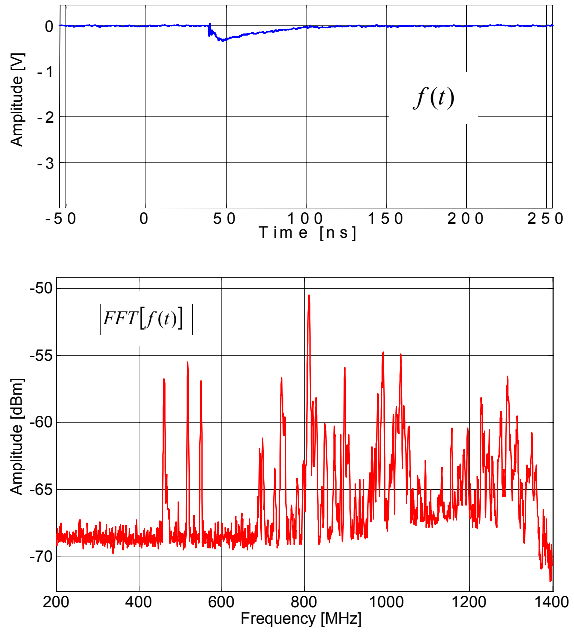

Fig. 4: Time domain measurement f(t) and power spectrum F(ω)

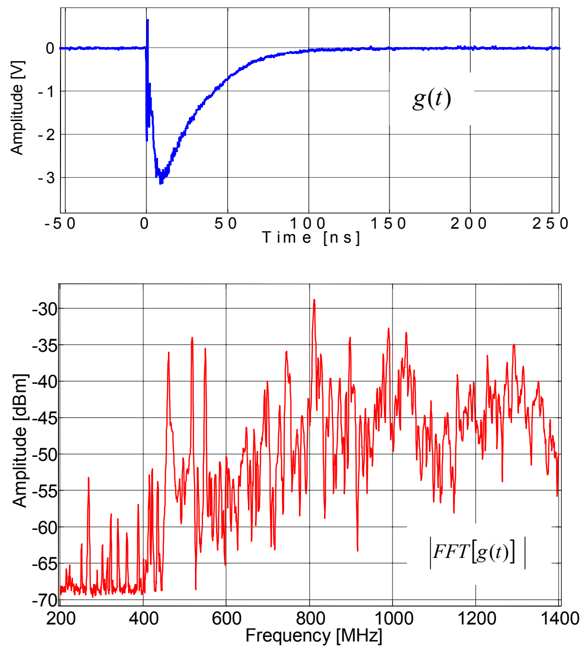

Fig. 5: Time domain measurement g(t) and power spectrum G(ω)

The time difference is measured in the time domain (Fig. 4 and Fig. 5) as $\Delta t = 39{,}3$ ns. These three power spectrums (Fig. 4, Fig. 5 and Fig. 6) are combined in the way presented in equation (6) using a software (Fig. 7).

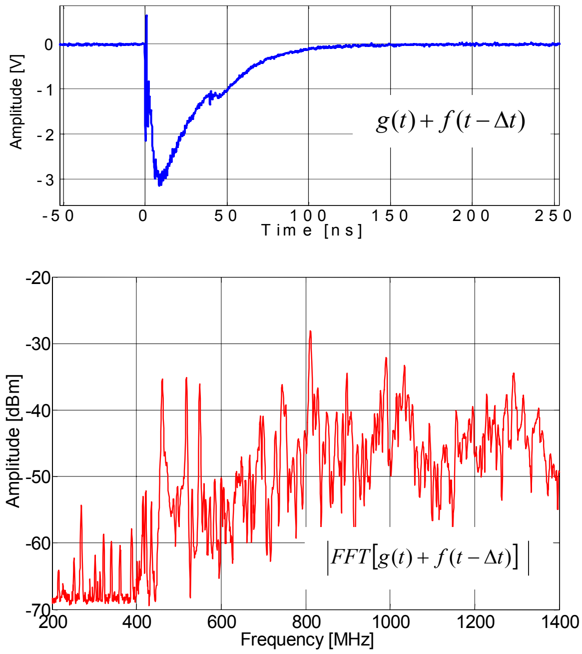

Fig. 6: Time domain measurement and power spectrum H(ω) of both signals (summed with the power splitter).

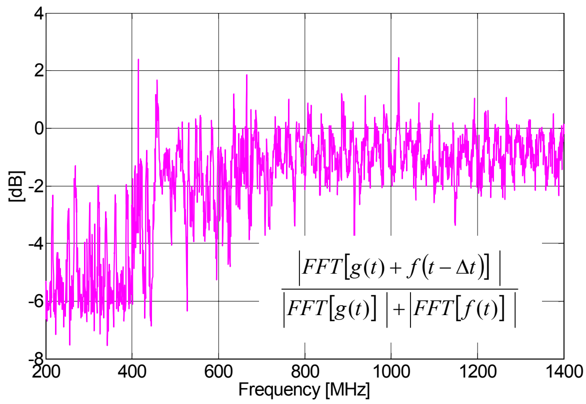

Fig. 7: The calculated combination of the power spectra

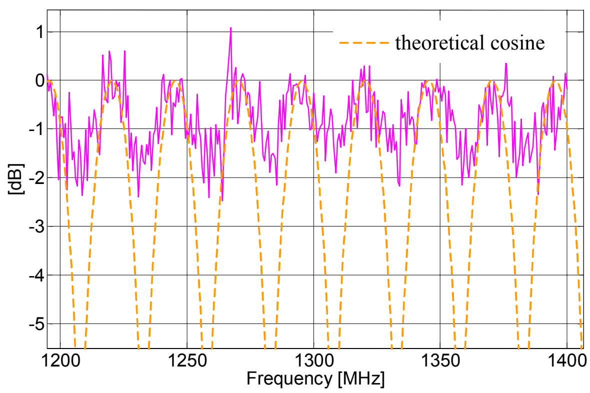

Fig. 8: Magnification of the power spectra (Fig. 7) with the theoretical cosine (6)

The signal in Fig. 8 shows an interference phenomenon and has equidistant minima. There are minima for example at 1210 MHz, 1235 MHz, and at 1260 MHz and further on. The characteristic frequency Δf equals 25 MHz and with the following equation

$$\Delta t = \frac{1}{\Delta f} \quad (8)$$

the estimated time difference (Δt) is 1/Δf = 40 ns.

The relation to the theoretical cosine shows that this interference phenomenon is useful although the signal f(t) is not exactly the same as g(t) caused by a attenuator.

Measurement at a real GIS The same interference effect can also be measured in an existing GIS. In the following different test setups with different types of GIS and PD-sources the interferences are presented as in Fig. 11.

Locating of a PD-source is possible in a 9 m long GIS (Fig. 9) for 550 kV in our lab with or without termination with wave impedance. The sensors are conventional UHF-PD-sensors. The connection cable to the sensors are different in length to increase the absolute Δt (Fig. 10). The PD-source is a pulse generator with an antenna (with a equivalent magnitude according to IEC 60270 q = approx. 50 pC).

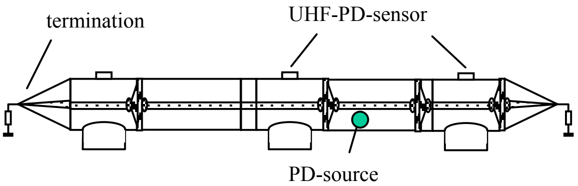

Fig. 9: 550 kV GIS with a PD-source and UHF-Sensors

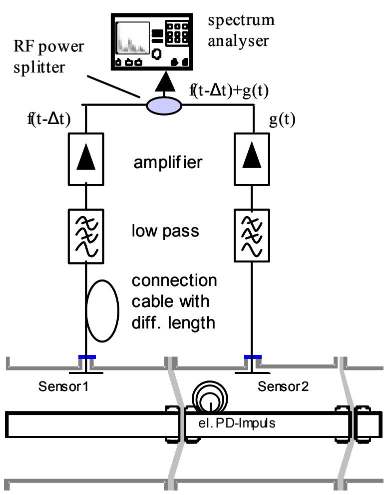

Fig. 10: Cross section of a GIS with corresponding test setup

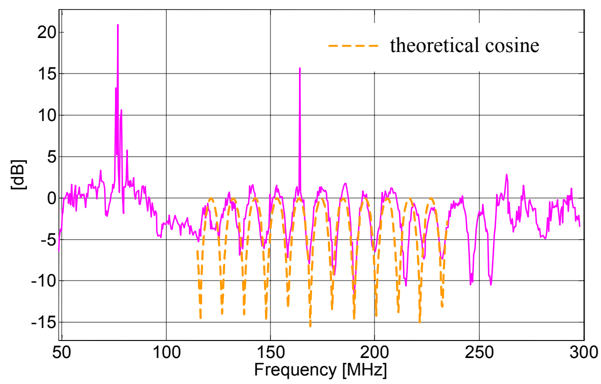

Fig. 11: Calculated combination of the power spectra of the measurement at the 550 kV GIS

The time difference is estimable in time domain measurements as Δt = 95.6 ns. The combined signal in Fig. 11 shows interference phenomena. The best matching with the theoretical cosine function is at Δf = 10.54 MHz and in respect of equation (8) Δt can be calculated as Δt = 94.9 ns. The interference phenomena in the calculated combination of the power spectra (Fig. 11) are clearly visible. At other GIS types and test setups these interferences are also recognizable (Fig. 13, Fig. 14).

The measurement of interference phenomena in a 3 m long GIS of 362 kV nominal voltage (Fig. 12) with conventional UHF-PD-Sensors and a protrusion on the outer conductor as PD-source (according to IEC 60270 q = approx. 150 pC) is shown in Fig. 13.

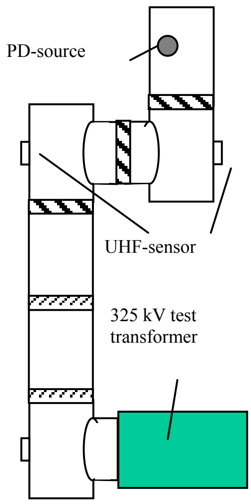

Fig. 12: GIS (362 kV) with PD-source

The best matching of the calculated combination with the theoretical cosine function (Fig. 13) is at Δf = 14.1 MHz and with equation (8) Δt is 70.7 ns (time domain measurements shows Δt = 73.5 ns).

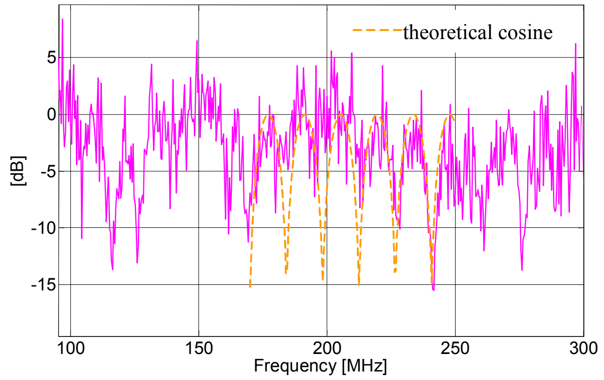

Fig. 13: The calculated combination of the power spectra of the measurement at the 362 kV GIS

The measurement of the interference phenomena in a complete bay of a 300 kV GIS is shown in Fig. 14. The two sensors are conventional UHF-PD-sensors at the bus bar and at the termination of the GIS. This distance corresponds to the distance of sensors at installed GIS. The PD-source is a pulse generator with an antenna.

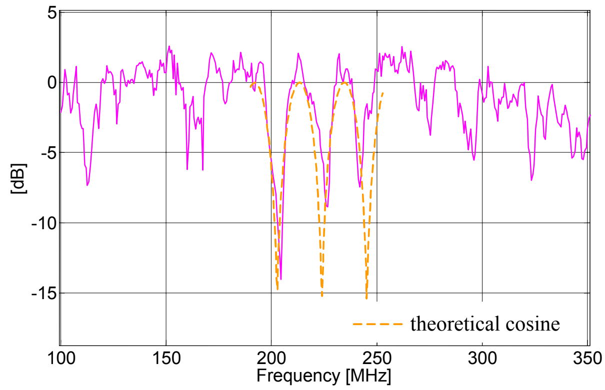

Fig. 14: Calculated combination of the power spectra of the measurement at the 300 kV GIS

The theoretical cosine function matches best at $\Delta f = 21.2$ MHz so Δt is measured as 47 ns (time domain measurement $\Delta t = 45$ ns).

Because of the more complex arrangement the evaluation of the measurement at 362 kV and 300 kV GIS (Fig. 13, Fig. 14) is not as simple as the measurement at the 550 kV GIS. The additional reflections of this arrangement in the GIS itself is the reason. The interpretation of these signals measured in a complex GIS will be the topic of future research work.

RESULTS AND DISCUSSION

This new method allows a cost-effective localization of PD in GIS in at least basic configurations or in gas-insulated lines (GIL). The interference phenomena of two sensor signals, which are summed, results in information about the time delay (Δt) between the signals. With this information a localization is possible.

Two similar sensor signals are required to receive useable results from this measurement procedure. Only the TEM-mode is useful for the measurement, because of dispersion effects at higher modes. These interferences can be measured at all different arrangements. However, the correct interpretation of these signals is in some cases a complex procedure, and requires sophisticated knowledge.

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