21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

D1-304

CIGRE 2012

Tuned Medium-Band UHF PD Measurement Method for GIS

Stefan M. Hoek*
OMICRON electronics
Austria

Stefan M. Neuhold
FKH Fachkommission für Hochspannungsfragen
Switzerland,

SUMMARY

In order to replace the lightning impulse test, a very sensitive PD-measurement is required for onsite tests of GIS [1]. The most sensitive UHF-PD-measurement technique consists of low-noise high –gain broadband amplifiers applied directly to the PD-sensors combined with the manual selection of possible resonant frequencies in the frequency spectrum for narrowband signal extraction with a bandwidth of some MHz. Further a correlation with the test voltage will lead to phase resolved signal display. The only disadvantage is the time consuming visual selection of the optimal centre frequency of the narrowband measurement system done sensor by sensor compared to broadband or fixed band measurement techniques. The broadband system design has the disadvantage of significantly reduced measurement sensitivity as soon as interfering frequencies are located within the measurement bandwidth. Beside this, in principle, the signal to noise ratio is lower for a broadband measurement system compared to a narrowband system. The narrowband system with fixed frequencies show poor or no sensitivity when the GIS resonant frequency caused by a PD source do not correspond with the narrow band measurement frequency or when interfering frequencies appear at the fixed measurement frequencies.

The tuned medium band UHF PD measuring system design consists of one or more manually pre-tuned band-pass filters with a bandwidth of 50 ... 150 MHz applied in a frequency range of approx. 100 ... 2000 MHz. The selection of the centre frequencies should be based on the individual resonant frequencies of the PD-sensors determined by the CIGRE sensitivity check [2] on site. The medium bandwidth allows to integrate the individually shifted resonant frequencies of a PD-signal at a PD-sensor within the measurement band, caused by different PD locations. Due to the wider bandwidth, the probability of missing PD-signals at a specific centre frequency is much lower than with the narrow band technique [3]. The evaluation of measurements carried out in different environment and different types of GIS showed a high possibility that a medium bandwidth is still narrow enough to avoid fix frequency disturbances by the use of a suitable centre frequency. Using several tuned frequency bands the probability of missing the resonance frequencies of a PD-signal is even lower and additionally allows to conduct a first coarse localization of the PD-source based on the frequency dependent damping of the PD-signal. The main advantage of the proposed design is the combination of simultaneous measurement with optimal sensitivity based on selective avoiding of fixed band interfering frequencies together with tuning into the most sensitive frequency band of each individual PD sensor of a GIS.

*Email: stefan.hoek@omicron.at

This results in an optimized system design for PD-measurements at on site tests of GIS and monitoring purposes and therefore in a high sensitivity of the measurement even in difficult situations due to interfering frequencies.

KEYWORDS

PD, Partial Discharge Measurement, UHF, On Site Tests, Gas Insulated Switchgear, GIS, Narrowband Broadband and Medium Band, Tuned Medium Band, PD-Monitoring

1 INTRODUCTION

The measurement of partial discharges is a worldwide accepted method for quality control in the factory and for on-site commissioning of high-voltage (HV) insulation systems [4]. Partial discharges are local electrical discharges which lead to a partial breakdown of the HV insulation [5]. Especially in gas-insulated systems (GIS) with SF_6 insulation, they generate electromagnetic waves in a very broad frequency spectrum due to their short rise time [6]. Protrusions and particles on insulators may generate low-level partial discharges but are easy detectable with lightning impulse tests. In order to replace the lightning impulse test, a very sensitive PD measurement is required for on-site tests of GIS [1].

Due to the usually significantly increased interference signal levels on site (compared to the optimized factory and laboratory environment), the PD measurement on site is usually carried out in the UHF frequency band. The common bandwidth of the UHF PD measurement method is approx. 100 MHz to 2 GHz. For the most common defect (moving particles) a high sensitivity is achieved. Especially with the variable narrow-band method, it is possible to specifically select frequency windows free of interference. Due to the underlying physics, it is not possible to calibrate this method similar to the IEC 60270 method. The CIGRE recommends a sensitivity check which verifies the number of UHF PD sensors in a GIS necessary to achieve a minimum sensitivity of 5 pC for a certain type of defect [2]. Details of the implementation of the sensitivity check are actually discussed in the CIGRE WG D1.25. For on-site commissioning testing of GIS, the UHF method has established itself as the standard method for PD measurements.

2 PD EMISSION AND TRANSMISSION

The extremely short rise times of PD signals in GIS result in frequency spectra extending to very high frequencies. Rise times from PD signals of protrusions down to 35 ps, corresponding to frequencies up to 10 GHz, have been verified [7]. For these high frequencies, the conductive structure works increasingly as an electromagnetic waveguide, whose cut-off frequencies depend on the dimensions and the inner structure of the GIS. Additionally to the basic TEM signal propagation mode, higher order modes (TE- and TM-modes) may propagate, depending on the geometry. The higher order modes propagate only above their cut-off frequencies (f_{CO}). In Figure 1, the cut-off frequencies of the first wave modes are shown for three different diameters, respectively different types of GIS.

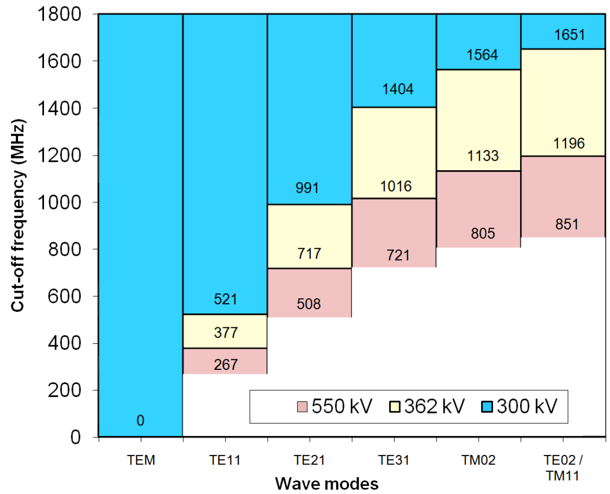

Figure 1: Cut-off frequencies (f_{CO}) within a GIS for 300 kV, 362 kV and 550 kV [8]

Each of these higher order modes are reflected at discontinuities, generate interference patterns and standing waves (resonances), and are damped by skin effect and lossy dielectric material. What is finally picked up at the broadband UHF PD sensor (built into the GIS) is the complex superposition of all modes, which result in a frequency spectrum with various resonances and frequency bands with highly different measurement sensitivity. As a result, the sensitivity of a PD-sensor is significantly dependent on the specific geometry of the signal transmission path between PD-sensor and PD-source [9]. In the terminology of the high-frequency technique, the GIS can be described as a heavily overmoded waveguide.

The TE- and TM-mode (often called higher modes) have H- and E-field components in the propagation direction and show an unsymmetrical field distribution (Figure 2) [10] in the transversal plain. This field distribution explains the transmission of the PD signal from source to sensor as a function of the angle φ between source position in relation to the sensor position.

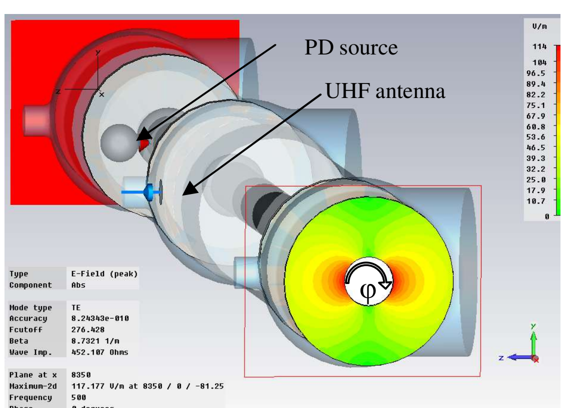

Figure 2: Electrical field distribution of TE_{11} wave mode inside GIS [11]

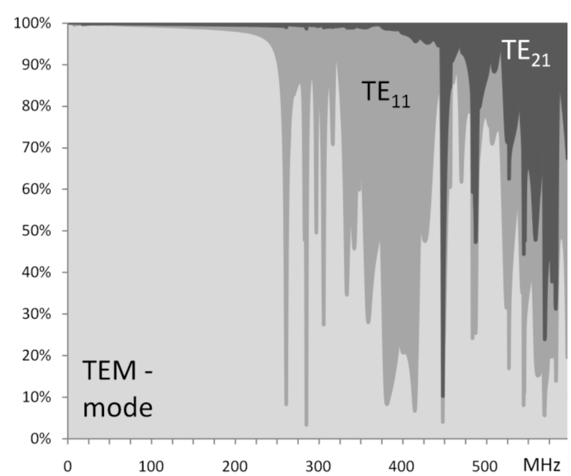

Figure 3: Share of the TEM-wave modes and higher modes (TE_{11} and TE_{21}) at the total transfer versus the frequency [11]

The analysis of the energy distribution of the different modes over the frequency range is shown in Figure 3. It reflects the importance of the higher modes for the signal propagation in the UHF range.

Due to the skin effect and losses at spacers, the propagating signals are damped; these effects are frequency-dependent. An example of a resulting spectrum is shown in Figure 4, (picture B) many individual frequency bands with narrowband resonances can be seen.

3 CURRENTLY USED UHF PD MEASUREMENT METHODS

Several types of UHF methods are applied on site:

- Tuned UHF narrowband measurement with variable center frequency
- UHF broadband measurement with fixed bandwidth
- UHF narrowband measurement with fixed frequency (or several fixed frequencies)

3.1 Tuned UHF narrowband measurement

Figure 4 shows the principle of the tuned UHF narrowband measurement with variable center frequency.

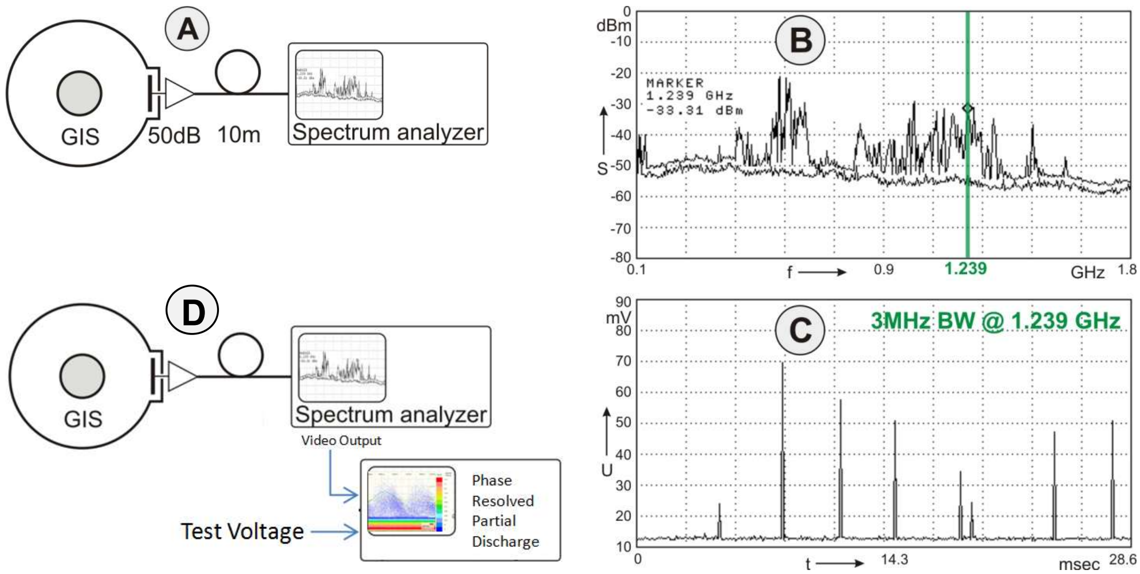

Figure 4: Example of a tuned UHF narrowband measurement with variable center frequency [12]

A preamplifier with a gain of 50 dB (0.1 – 2 GHz) is connected directly to the UHF sensor in order to prevent loss of sensitivity and reduce effects of external noise over the length of the cable connected to the measurement equipment (Figure 4A). Figure 4B shows the spectrum analyzer display of the measurement window of 0.1 - 1.8 GHz. The lower trace shows the noise floor, the upper trace shows the mixture of PD signals along with sporadic external interference, displayed linearly in frequency and logarithmically in amplitude (peak hold measurement with one minute integration time).

The frequency window in which PD can be measured depends on the combination of the defect and the employed sensor. Ideally, a suitable measurement frequency window can be identified by simple observation in which a high signal-to-noise ratio (SNR) results in high measurement sensitivity.

Once such a window is found, the spectrum analyzer’s center frequency is centered on it, the bandwidth is set to e.g. 3 MHz, and the amplitude scaling is switched to linear (Figure 4C). The result is that the time-domain PD signal is coupled out at a measurement frequency in the UHF region with a high SNR. This signal can then be displayed on a conventional PD measurement system which is synchronized to the high-voltage test waveform.

Once a phase-correlated pattern can be observed (Figure 4D), it means a PD source synchronous to the test voltage is active and should be further investigated. If no phase-correlated pattern can be found, it is probable that the signal is an uncorrelated external interference which is irrelevant. Even under difficult conditions with high levels of ambient interference, with some practice suitable frequency windows with good SNR can be found. Standardized equipment and methods can be employed to enable reproducible results across different measurement configurations and over the lifetime of the GIS to be obtained.

The PD-signal source of the given example (Figure 4) was a 10 mm long aluminum particle in a circuit breaker in a bus bar coupler of a 132 kV GIS. The extinction voltage was less than 35 kV. The phase-to-ground operating voltage is 76 kV. The measurements shown were made at 55 kV.

3.2 Broadband UHF measurement

Broadband UHF measurement with fixed bandwidth is widely used especially for monitoring systems. A schematic diagram of the PD signal spectrum measured across a bandwidth of several hundred MHz is shown in Figure 5.

Here, the fixed broadband frequency spectrum is directly integrated and the signal variation displayed directly in phase-resolved PD pattern format. The frequency-domain amplitude envelope is not visible, only the phase-resolved PD pattern is seen.

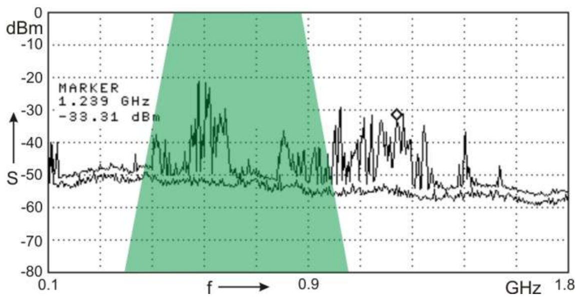

Figure 5: Bandwidth of fixed broadband UHF method (schematic example) [12]

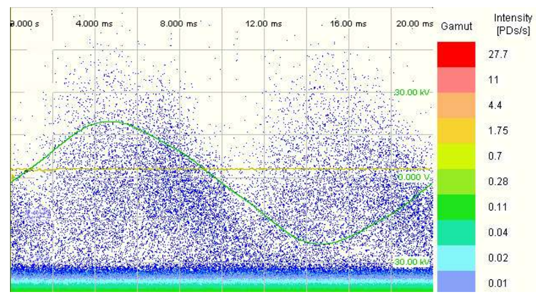

Figure 6: PRPD diagram of a broadband measurement of a moving particle

The example in Figure 6 shows the phase-resolved partial discharge (PRPD) pattern of a particle at a bus bar of a 362 kV GIS. The measurements shown were made at 17 kV.

A disadvantage of this method is the lower SNR. Even narrowband disturbances lead to a reduced sensitivity in a broadband measurement system. Advantages of this method are the relatively easy technical realization and the low effort for choosing the settings compared to the previously described narrowband method.

3.3 Narrowband UHF measurement with fixed frequencies

Figure 7 shows a schematic diagram of the measurement domain of a narrowband UHF measurement with fixed frequencies. One or more narrow-frequency windows are sampled and their output magnitude variation displayed directly as phase-resolved PD. Again, the frequency-domain spectrum is not visible here. There is the danger that the narrow-frequency window may not exactly overlap the specific resonance frequencies of the received PD signal. In this case, it is possible that even a PD source close to the sensor may not be seen.

The advantage of the fixed-frequency UHF methods is the possibility to display the phase-resolved pattern of multiple PD sensors simultaneously. The disadvantage of the fixed frequency methods is that strong external interference sources such as radar, mobile telephones, corona, etc. cannot be selectively tuned out which result in a reduced sensitivity.

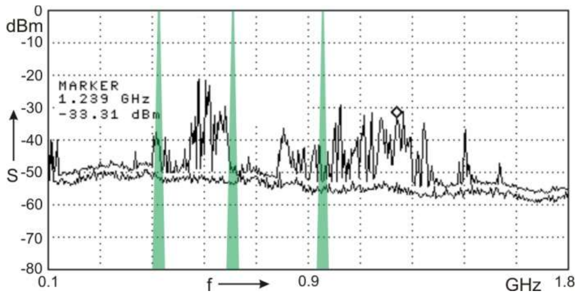

Figure 7: Width of fixed narrowband UHF method (schematic example) [12]

Compared to the fixed narrowband UHF method the tuned narrowband UHF method shows significant advantages. In areas with high levels of external interference, i.e. large substations or in built-up industrial or urban areas, the tuned narrowband UHF method demonstrates a significant advantage in sensitivity due to selective avoidance of interference bands and thus represents the most sensitive UHF PD measurement method. In combination with low-noise broadband amplifiers applied directly to the PD sensors and the manual selection of possible resonant frequencies in the frequency spectrum for narrowband signal extraction and further phase correlated signal display even very low-level PD signals can be detected.

The only disadvantage is the time consuming visual selection of suitable measurement frequencies during the HV test at each individual sensor which leads to a sequential measurement procedure, compared to the possibility of simultaneous check on many sensors for the fixed-frequency UHF methods.

4 TUNED MEDIUM-BAND UHF METHOD

The tuned medium-band UHF PD method combines the advantages of simultaneous measurements on many sensors with the individual optimizing of the signal to noise ratio at each PD sensor.

The tuned medium-band UHF PD measuring system design consists of one or more manually pre-tuned band-pass / receivers filters with a bandwidth of 50 to 150 MHz applied in a frequency range of approx. 100 to 2000 MHz (Figure 9). Carried out previous to the HV test, the selection of the center frequencies should be based on the individual resonant frequencies of the PD sensors determined by the CIGRE sensitivity check on site. The medium bandwidth allows integrating the individually shifted resonant frequencies of a PD signal at a PD sensor within the measurement band [12].

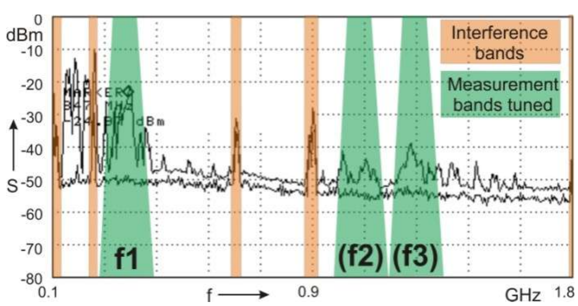

Figure 8: Signal relationships of proposed tuned medium-band UHF method (schematic example) [12]

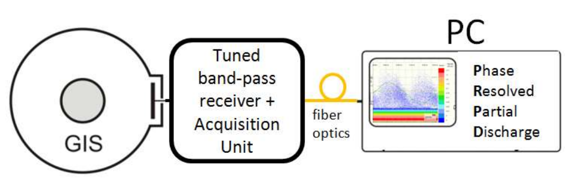

Figure 9: Example of a measurement setup for the tuned medium-band UHF method with galvanic insulation via fiber optics to reduce the impact of disturbances

Typical interferences in the UHF frequency range are smaller than some ten MHz. In Figure 8, they are marked with orange color. The measurement bandwidth has to be smaller than the typical distances of the interference frequencies. In Figure 8, the sensitive measurement ranges (excited with a pulse generator during a sensitivity check) are marked in green.

Based on the evaluation of several hundred spectra, a bandwidth of 50 - 150 MHz turned out to be a good compromise between selective measurement and reliable usage of sensitive resonance frequencies. Using one or more tuned medium-frequency bands, the whole measurement frequency range can be optimally configured and observed. Additionally, the method enables with good probability to give a first coarse localization of the PD source based on the frequency-dependent damping of the signals.

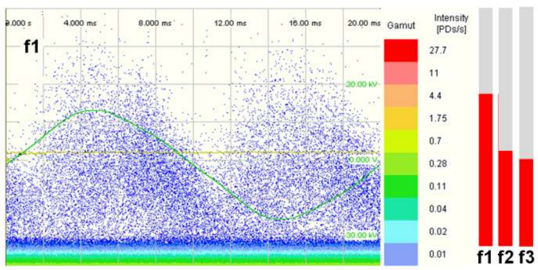

Figure 10: Example of possible measurement data display of one PD sensor of the proposed tuned medium-band UHF method (schematic example).

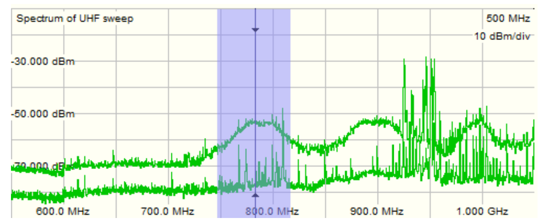

Figure 11: Example of a spectrum of PD signal (upper function) and continue wave disturbance (lower function). The used measurement band marked in blue.

For the generation of the phase-correlated PD patterns, the different frequency bands can be displayed individually, summed together or combined with e.g. histogram and bar graph indication for a quick overview.

Figure 10 shows an example of a possible display of the measurement data of one sensor. The signal of the measurement band f1 is displayed in phase-correlated histogram mode while the signal level of all three measurement bands (f1…f3) is displayed in bar graph mode. When the measurement data (e.g. displayed like in Figure 10) of multiple PD sensors are displayed together on one display, specifically the bar graph indication of the three measurement bands of each individual PD sensor enables a coarse localization of the PD source based on the frequency-dependent damping of the signal.

In contrast to the narrowband method with fixed frequency, the medium-band method integrates with good probability those signal frequency components which have been shifted due to the difference in location between the actual PD source and the point of signal injection used to perform the CIGRE sensitivity check. The magnitude of the detected signal depends strongly on the location and to a minor degree on the orientation of the defect and the coupler [2]p77.

The main advantage of the proposed design is the combination of high sensitivity and the ability to select out interference signals while being able to tune to the most sensitive resonant frequencies of each PD sensor (Figure 11). A further advantage is the reduced time required for the visual selection of suitable measurement frequencies during the HV test. It can be chosen between (e.g. three) preselected measurement bands, which allows the parallelization of the measurement procedure and there for simultaneous check of multiple PD sensors.

This results in an optimized system design for PD measurements, both for on-site tests and monitoring, enabling high-sensitivity measurements even in difficult situations with the presence of strong interference sources.

5 CONCLUSION

Among the present UHF methods, the narrowband method with visual selection of the measurement frequency together with a broadband preamplifier directly mounted at the PD sensor allows the most sensitive measurements. Due to the frequency window selection process, the effort and the need of experience to practice this method is high.

The proposed tuned medium-band UHF method offers the possibility to selectively avoid interfering frequencies but also not to miss resonant frequencies at a specific PD sensor (which are interdependent on the defect and its location) due to sufficient bandwidth. A pre-tuning of each individual sensor location based on the second step of the CIGRE sensitivity check on site allows simultaneous measurements of many sensor locations with optimized settings.

6 ACKNOWLEDGEMENT

The authors gratefully acknowledge both fruitful technical discussions and consultation in respect of high-frequency theory from Daniel Treyer, PSI.

7 BIBLIOGRAPHY

[1] CIGRE Joint Working Group 33/23.12 Insulation co-ordination of GIS; return of experience on site tests and diagnostic techniques; Electra No 176, February 1998

[2] CIGRE task force 15/33.03.05, "Partial discharge detection system for GIS: Sensitivity verification for the UHF method and the acoustic method", Electra No 183, April 1999, p75 - 87

[3] M.D. Judd, O. Farish, B.F. Hampton "The Excitation of UHF Signals by Partial Discharges in GIS" IEEE Trans. Dielectrics and Electrical Insulation, Vol. 3, No. 2, April 1996

[4] D. König and Y.N. Rao: "Partial Discharges in Electrical Power Apparatus", VDE 1993

[5] IEC 60270, "High-voltage test techniques – Partial discharge measurement", Version 2000, 3rd Edition

[6] M.D. Judd, S. Meijer and S. Tenbohlen, "Sensitivity check for RF PD detection for power transformers," IEEE Conference on Condition Monitoring and Diagnosis (CMD), Peking, China, April 21-24, 2008, paper No. K1-03

[7] A.J. Reid, M.D. Judd; "High Bandwidth measurement of Partial Discharge Pulses in SF_6"; 14th ISH Beijing, China, August 25-29 2005; G-012

[8] S.M. Hoek, U. Riechert, T. Strehl, K. Feser, and S. Tenbohlen, "New Procedures for Partial Discharge Localization in Gas-Insulated Switchgears in Frequency and Time Domain", 15th ISH Ljubljana / Slovenia, August 2007

[9] G.J. Behrmann, S.M. Neuhold, R. Pietsch, „Results of UHF measurements in a 220-kV-GIS Substation during on-site commissioning tests; 10th ISH Montreal; August 1997

[10] R. Kurrer, K. Feser, "The Application of Ultra-High-Frequency Partial Discharge Measurements to Gas-Insulated Substations", IEEE Transactions on Power Delivery, Vol. 13, No. 3, July 1998

[11] S.M. Hoek, M. Koch and M. Heindl, "Propagation Mechanisms of PD Pulses for UHF and Traditional Electrical Measurements" IEEE Conference on Condition Monitoring and Diagnosis (CMD), Tokyo, Japan, Sept 06-11, 2010, paper No. C2-02

[12] S.M. Neuhold, "On site tests of GIS", High-Volt Kolloquium '11, Dresden, Germany, May 2011