TUNED MEDIUM-BAND UHF PD MEASUREMENT SYSTEM FOR GIS

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Abstract: Due to the required reliability and long life-cycle of GIS, all quality control measures are of high importance, especially the partial discharge (PD) acceptance test on-site. AC test combined with a sensitive PD measurement has become the standard test procedure. The basic theory and measurement techniques of ultra high frequency (UHF) PD measurement methods are shown. To achieve optimum sensitivity, interference suppression, and simultaneous measurement at multiple sensors, a tuned medium-band UHF method is proposed.

1 INTRODUCTION

The measurement of partial discharges is a world-wide accepted method for quality control in the factory and for on-site commissioning of high-voltage (HV) insulation systems [1]. Partial discharges are local electrical discharges which lead to a partial break down of the HV insulation [2]. 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 [3]. 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 onsite tests of GIS [4].

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 [5]. 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 [6]. For these higher frequencies the conductive structure works increasingly as an electromagnetic wave guide, who's 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_c). In Figure 1 the cut-off frequencies of the first wave modes are shown for three different diameters, respectively different types of GIS.

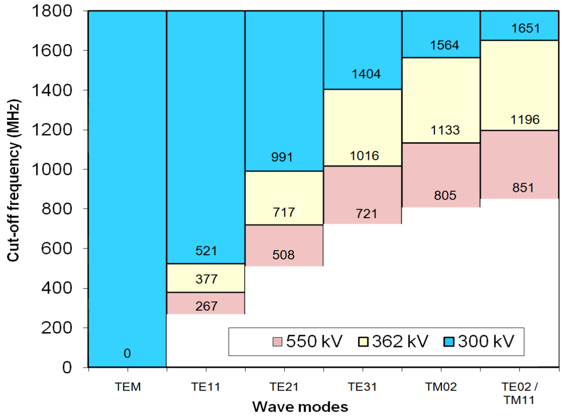
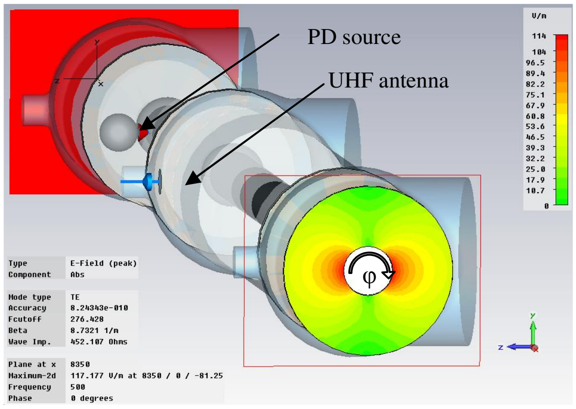


Figure 1: Cut-off frequencies (f_c) within a GIS for 300 kV, 362 kV and 550 kV [7]

Each of this 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.

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 in the transversal plain an unsymmetrical field distribution (Figure 2) [8]. 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.



Type E-Field (peak)
Component Abs

Mode type TE
Accuracy 8.24343e-010
Fcutoff 276.428
Beta 8.7321 1/m
Wave Imp. 452.107 Ohms

Plane at x 8350
Maximum-2d 117.177 V/m at 8350 / 0 / -81.25
Frequency 500
Phase 0 degrees

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

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.

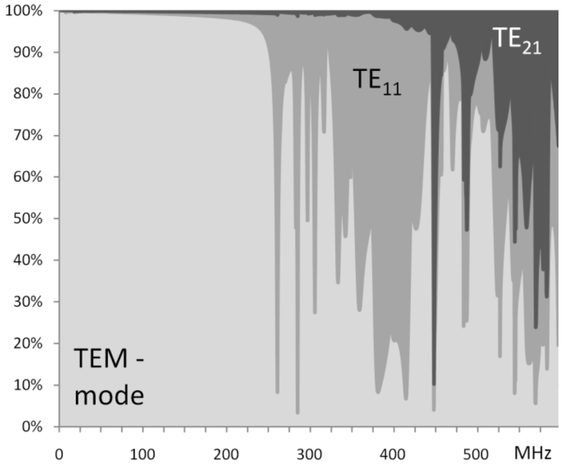


Figure 3: Share of the TEM-wave modes and higher modes (TE_{11} and TE_{21}) at the total transfer versus the frequency [9]

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 centre frequency
- UHF broadband measurement with fixed bandwidth
- UHF narrowband measurement with fixed frequency (or several fixed frequencies)

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

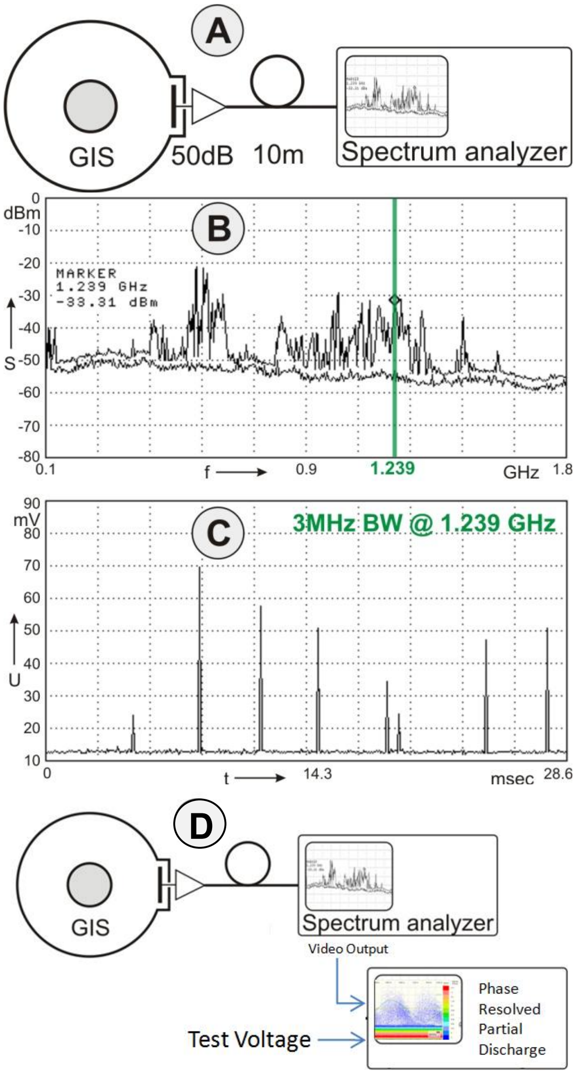


Figure 4: Example of a tuned UHF narrowband measurement with variable centre frequency

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 1 minute integration time).

The frequency window in which PD can be measured is depending 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 was an 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.

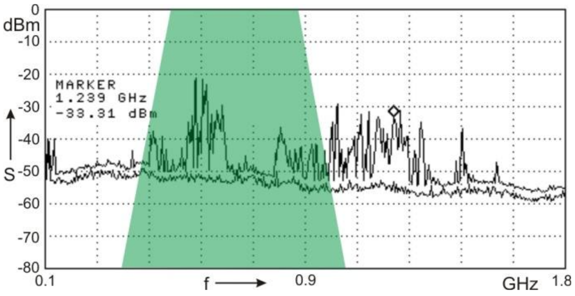


Figure 5: Bandwidth of fixed broadband UHF method (schematic example)

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

Here the fixed broad-band 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.

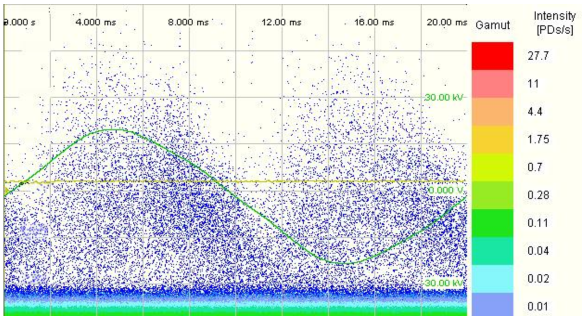


Figure 6: PRPD-Diagram of a broad-band measurement of a moving particle

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.

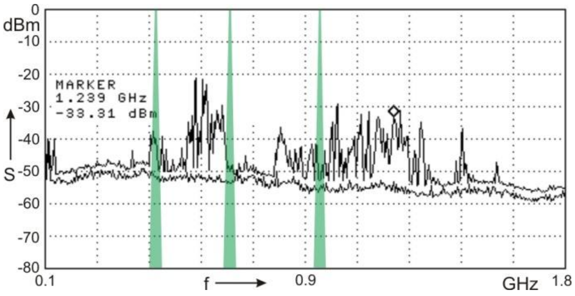


Figure 7: width of fixed narrowband UHF method (schematic example)

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.

In areas with high levels of external interference, i.e. large substations or in built-up industrial or urban areas, the variable frequency narrowband method demonstrates a significant advantage in sensitivity 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 several manually tuned band-pass/receivers filters with a bandwidth of 50 - 150 MHz applied in a frequency range of approx. 100 to 2000 MHz. 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 to integrate the individually shifted resonant frequencies of a PD signal at a PD sensor within the measurement band [10].

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.

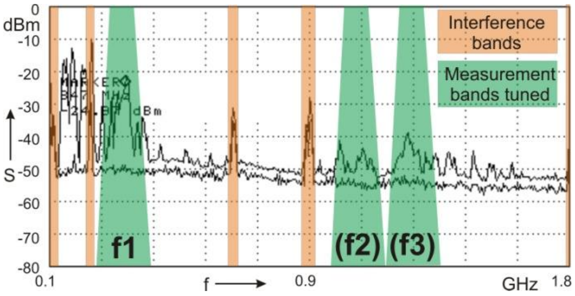


Figure 8: Signal relationships of proposed tuned medium-band UHF method (schematic example) [10]

Based on the evaluation of several hundred spectra's, a bandwidth of 50 - 150 MHz turned out to be a good compromise between selective measurement and reliable usage of sensitive resonance frequencies

Using several tuned medium frequency bands, the whole measurement frequency range can be optimal 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.

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.

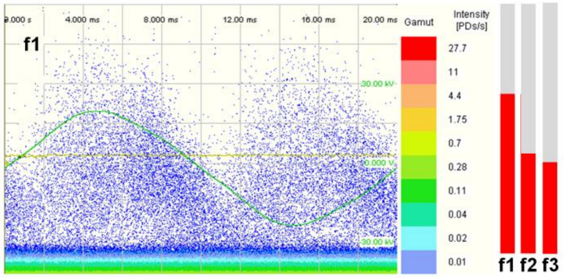


Figure 9: Example of possible measurement data display of one PD sensor of the proposed tuned medium-band UHF method (schematic example). Multiple PD sensors can be displayed together on one screen for quick overview.

Figure 9 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) are displayed in bar graph mode.

When the measurement data (e.g. displayed like in **Figure 9**) of multiple PD sensors are displayed together on one display, specifically the bar graph indication of the 3 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 [5]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.

A further advantage is the reduced time consumption require 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

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