

# PERFORMING SENSITIVE UHF PARTIAL DISCHARGE MEASUREMENTS WITH UNKNOWN SENSOR CHARACTERISTICS

Dipl.-Ing. Falk Werner, Doble Engineering Co.  
M. Sc. Philipp Wenger, Transnet BW GmbH

## ABSTRACT

This paper provides an overview of the challenges of UHF PD measurements in the field, measurement approaches using different types of detectors. Particular focus is laid on measurements performed on sensors with unknown transfer function characteristics on Gas Insulated Switchgear, the influence of external noise from radio signal sources on the measurements, and ways to mitigate the impact of noise on the measurement. It shows advantages and disadvantages of different measurement methods, as well as their ideal use cases. Two case studies of GIS UHF PD Measurements are presented.

## INTRODUCTION

Ultra-High-Frequency (UHF) Partial Discharge (PD) measurements are a well-established tool for in-service assessments of the insulation system condition of high voltage assets. They are commonly used in transformer and Gas Insulated Switchgear (GIS) assessments, as well as for substation surveys. The basic principle of UHF PD measurements is to measure radio frequency emissions that are generated by the discharge events which take place inside a test object by utilizing appropriate sensors and detection circuits.

This paper reviews general UHF measurement aspects, UHF signal characteristics, signal analysis, the impact of external noise signals, and different types of UHF measurement approaches taken to assess insulation system health.

## UHF MEASUREMENTS

UHF PD measurements can be performed using a wide range of sensors to detect emissions of partial discharge in the radio frequency, high, very high, and ultra-high frequency ranges. In UHF PD measurements, any type of sensor capable of detecting PD at frequencies greater than 100MHz and less than 2GHz can be utilized to detect electromagnetic emissions of PD. Typical test objects for such UHF measurements are gas insulated switchgear (GIS) with internal or external (mainly employed in retrofit applications) UHF antennas or power transformer with suitable UHF sensors.

For diagnostic purposes, acquired signals are typically analyzed for their phase resolved partial discharge (PRPD) characteristics. Figure 1 and Figure 2 show examples of GIS and transformer drain valve sensor arrangements for UHF Measurements with generic PD detectors.

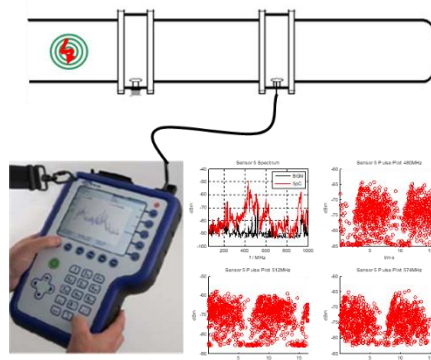
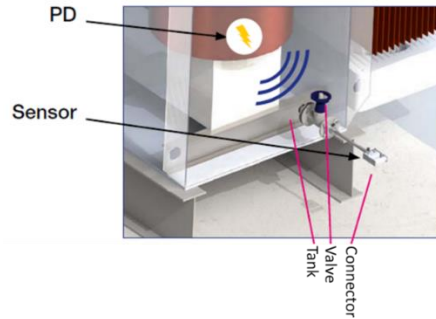


Figure 1: UHF PD Measurement on GIS with Built-in Antennas



**Figure 2: UHF Drain Valve Antenna**

The basic principle is to place an antenna inside the test object, GIS or transformer tank, which serves as a sensor for UHF PD signals originating from within the test object,

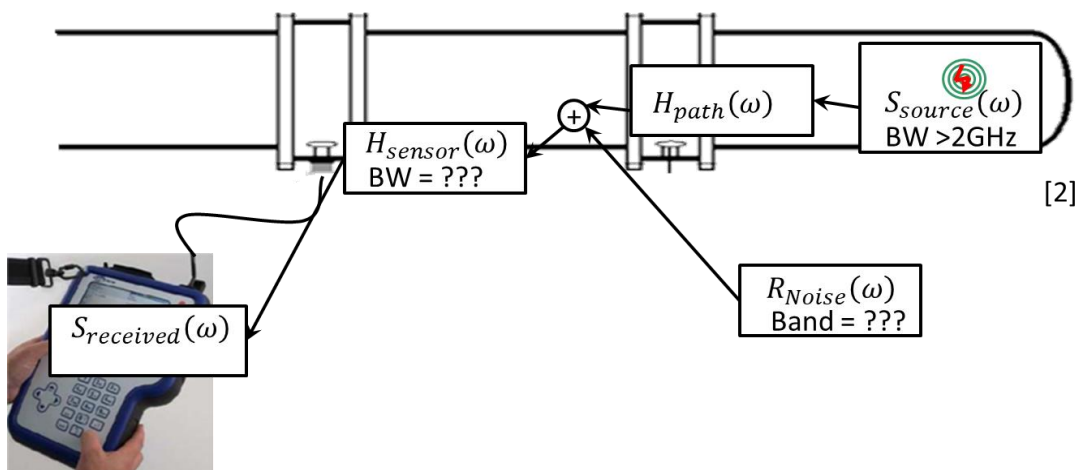
### UHF SIGNAL CHARACTERISTICS

For all UHF measurements it is important to understand the signal characteristics as well as the characteristics of the measurement circuits which are used. In any measurement, the measurement system is not only measuring signals of interest, but may also be detecting nuisance signals, noise, and disturbances, which affect the measurement sensitivity, reliability, and accuracy.

Knowing the characteristics of the system and acquired signals allows to adjust the measurement circuit and detector characteristics to be tweaked in order to achieve maximum sensitivity and reliability of the measurement.

Figure 3 shows the signal propagation path of a UHF signal within a GIS. While this example uses GIS, the general measurement characteristics, influence of the propagation path, addition of external noise, and sensor characteristics is the same for all UHF measurements.

$$S_{received}(\omega) = (S_{source}(\omega) \cdot H_{path}(\omega) + R_{Noise}) \cdot H_{sensor}(\omega)$$

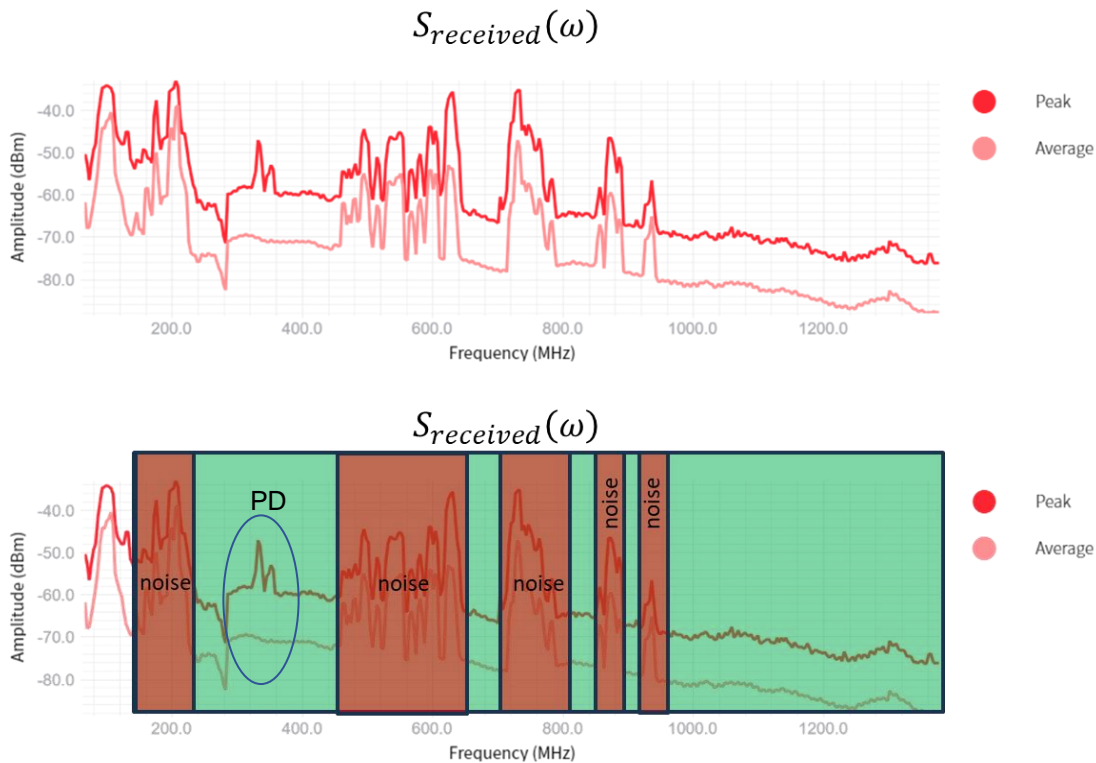


**Figure 3: UHF Signal Propagation Path (Source to Measurement System)**

In the example above the signal characteristics of a received signal  $S_{received}(\omega)$  – with  $\omega$  being the frequency – are described in the frequency domain as the product of the source signal frequency content  $S_{source}(\omega)$  multiplied/filtered with the propagation path transfer function  $H_{path}(\omega)$ , added noise  $R_{noise}(\omega)$ , multiplied/filtered with the sensor transfer function  $H_{sensor}(\omega)$ .

The PD source typically has a very wide bandwidth, which is then limited by the propagation path and sensor characteristics. The bandwidth and magnitude of noise signals contributing to the measurements is not predictable and has to be taken into account for the measurements.

UHF measurements are done in a frequency range between 100MHz and 2GHz. While PD signals fall within this bandwidth, there may also be significant noise and nuisance signals present. Figure 4 shows the spectrum acquired during a UHF GIS PD measurement. The detector acquired the peak and average spectra of the signals present on an internal UHF PD sensor in a frequency range between 100 MHz and 1300 MHz. The dark red line is the peak, the light red line is the average signal magnitude spectrum. A divergence between peak and average is indicative of pulse shaped signals, such as PD, being detected in a specific frequency range. Peak and average running parallel or rising together in certain frequency ranges indicate the presence of modulated signals, such as radio, television, VHF communication, GSM etc.

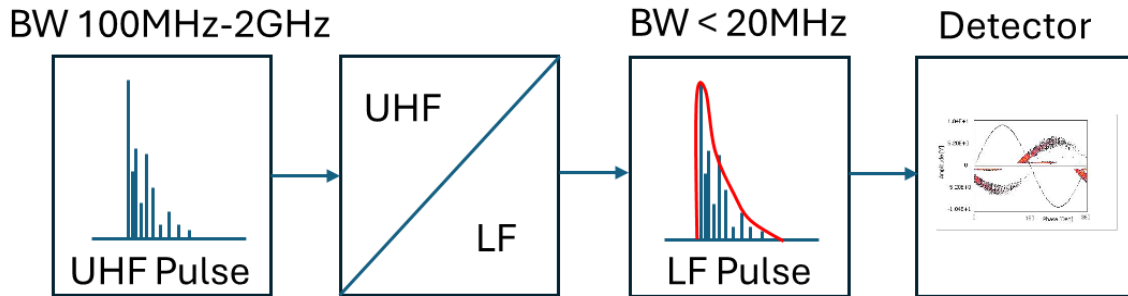


**Figure 4: UHF PD Measurement Signal Spectrum (PD and Noise)**

In the measurement data above, certain bands are highlighted in which nuisance signals or noise are present. These can be identified by both peak and average spectra rising. The sensor is detecting PD around 350 MHz, where there is a rise in peak while the average spectrum does not rise. This is due to the duration of the PD pulses being very short (ns or us) relative to the time frame of the evaluation (typically 40 ms). In the data above it is obvious that the magnitude of the PD signal around 350 MHz is at lower or similar levels as the magnitude of the nuisance signals at different frequencies. This circumstance needs to be taken into account when using different measurement methods of UHF measurements.

## BROAD-BAND UHF TO LF CONVERTED DETECTION

Broad-Band UHF detection using frequency shifters, frequency converters, integrators, low-pass filters etc. have been effectively used in UHF measurements since the 1990s. UHF measurement technology, such as GHz spectrum analyzers or oscilloscopes, have long been cost prohibitive to be adopted into PD measurements, and frequency shifters allow for a simple and straightforward way of making UHF signals detectable with detectors of bandwidth <30 MHz. The purpose of a frequency shifter is to make a UHF pulse present at higher frequencies >100 MHz measurable using a low bandwidth detector that operates at lower frequencies. The basic operational principle of a frequency shifter is depicted in Figure 5.



**Figure 5: UHF to LF Converted PD Measurement – Operational Principle**

A high frequency signal with a large bandwidth is passed through a frequency conversion circuit and the result of the processing/filtering is a signal with a significantly lower bandwidth (red signal) as a function of the incoming signal. This lower bandwidth signal then can be processed by a detector with a bandwidth of less than 20MHz, which is used to analyze the PRPD characteristics of the observed signals.

While this method allows for simple and straightforward utilization of LF and UWB detectors to measure UHF PD pulses, enabling broad deployment and very cost-effective utilization of UHF, the presence of nuisance signals in the passband of the conversion circuit may negatively affect the sensitivity of such measurements.

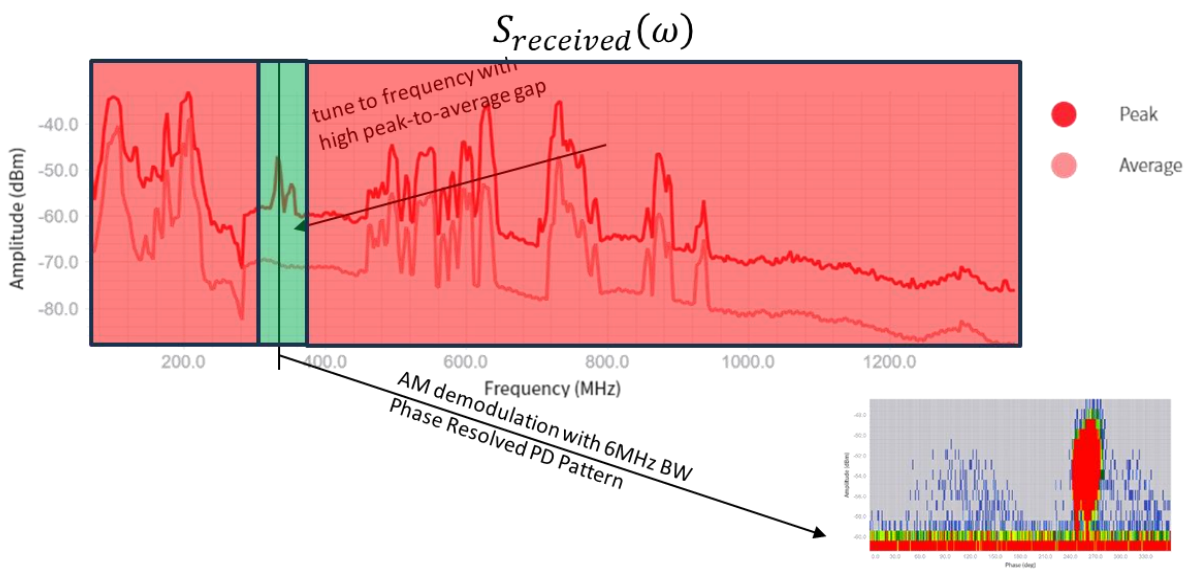
Utilizing such a circuit on the scenario shown in Figure 4 and leaving the passband wide enough for the nuisance signals to contribute to the measurement may mask the PD activity observed around 350 MHz. Knowing the transfer function of the utilized sensors and the frequency ranges of nearby nuisance signal sources allows the user of such systems to narrow the passband for frequency conversion. In the present case, adding a 300 MHz to 400 MHz bandpass would allow for the detection of the observed PD using a wide band UHF detector.

## NARROW-BAND UHF DETECTION

Narrow-band UHF measurements were introduced in the early 2000s by using analog satellite TV tuners to demodulate PD signals at higher frequencies with adjustable bandwidths. The measurement circuit works in a similar fashion to a UHF Spectrum Analyzer in Zero-Span Mode. In essence, UHF PD detectors that use narrow band technology are comparable to AM radios which can be tuned to specific frequencies and demodulate the signal with a specific bandwidth at these frequencies. The demodulation (via peak detection) of the UHF signal at a specific frequency is passed through a PD detector to determine the required pulse parameters for analysis. The bandwidth of the PD signal is typically between 6 MHz and 56 MHz, while bandwidth closer to 6 MHz are preferred, as less of the overall signal spectrum and hence less of potential noise signals contribute to the peak-detected signal.

The benefit of narrow-band PD detectors is that they can be tuned to frequencies in which the used PD sensors are sensitive, and away from frequencies in which noise is present. Hence UHF narrow band PD detectors have a significant advantage when it comes to sensitivity at the expense of a more complicated measurement procedure.

To illustrate the measurement principle, we look at the example spectrum from Figure 4 again. Figure 6 shows the acquired spectrum, areas of nuisance (red) and PD (green) signals, as well as the PRPD data acquired by a narrow-band UHF tuner tuned to the frequency where peak and average spectra diverge. The bandwidth of this measurement is 6 MHz, and no signals outside this band contribute to the PRPD measurement. The result is a clear PD pattern with no contribution of nuisance signals, in spite of the nuisance signal's energy being higher across the spectrum than that of the PD signal of interest.



**Figure 6: UHF Spectrum with PD and Nuisance Signal, Narrow-Band Tuning, PRPD**

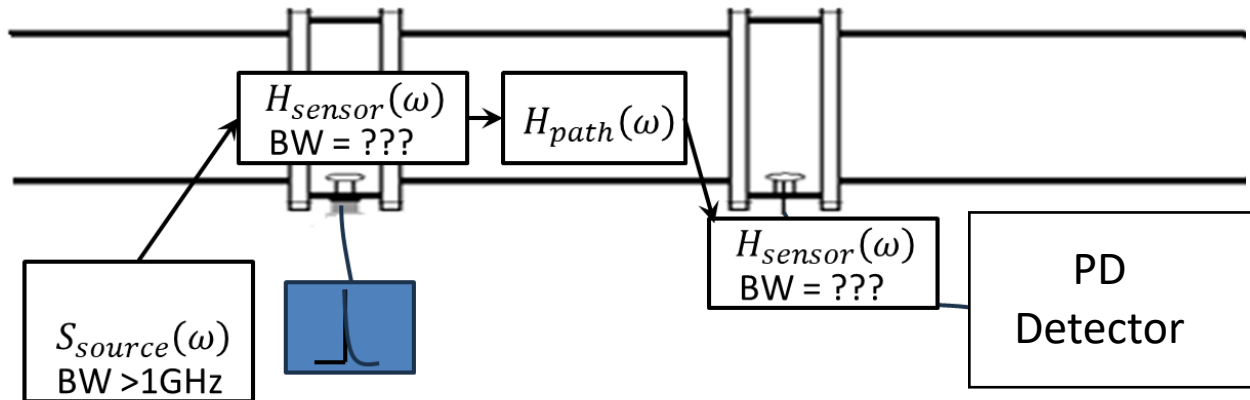
The magnitude and energy of the PD within the overall signal is significantly lower than that of the nuisance signals and it may only be detected with narrow-band tuning, ignoring nuisance signals in adjacent bands.

Using narrow band detectors typically results in a more expensive measurement setup and complex measurement procedure, but it provides significant benefits in terms of increased detection sensitivity.

## DETERMINATION OF SENSOR CHARACTERISTICS WITH SENSITIVITY CHECK

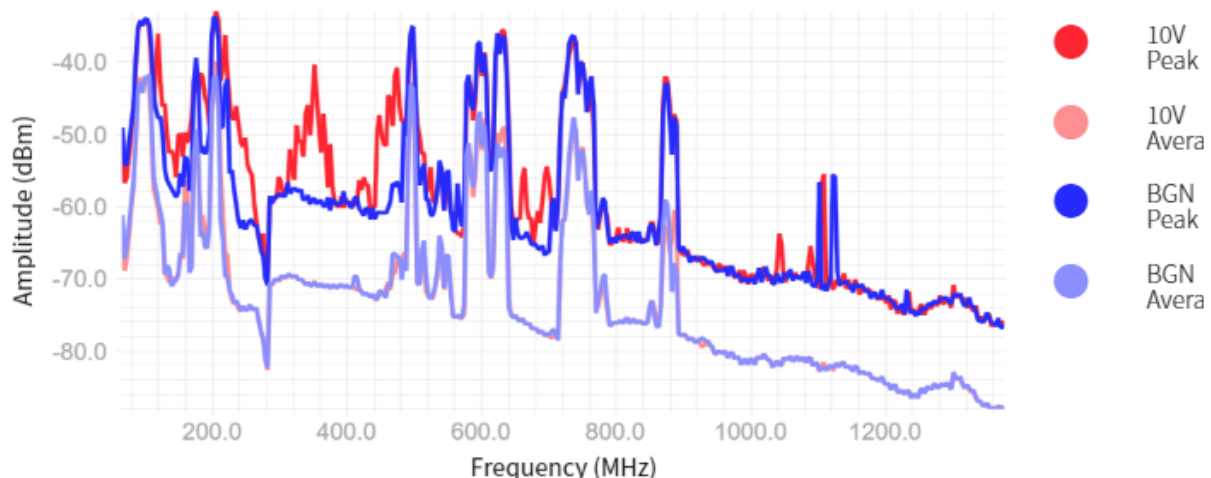
To determine the frequency transfer function of UHF antennas in setups with multiple UHF antennas, a UHF sensitivity check can be performed using a UHF pulse generator. Figure 7 shows the basic sensitivity check principle and signal path characteristics. The goal is to test the functionality of the sensors and to determine the frequency transfer function of the system by measuring a UHF pulse injected via one UHF antenna using a pulse generator, measuring the arriving pulse at another antenna.

The received signal characteristics  $S_{PD\text{detector}}(\omega)$  at the detector are a product of the pulse generator signal  $S_{source}(\omega)$  multiplied/filtered with the propagation path transfer function  $H_{path}(\omega)$ , added noise  $R_{noise}(\omega)$  (not shown in graph), again multiplied/filtered with the sensor transfer function  $H_{sensor}(\omega)$ .



**Figure 7: UHF Sensitivity Check Principle**

By comparing the acquired peak and average spectra acquired with and without active pulse generator, conclusions regarding the transfer function of the UHF sensors can be drawn. Figure 8 shows an example of acquired signals in a setup such as the one described in Figure 7. The dark and light red spectra are the peak and average spectra acquired with a 10 V UHF pulser (repetition rate = 120 Hz) injecting a signal at one sensor, while the measurement system is measuring the spectrum on another sensor. The dark and light blue spectra are the peak and average spectra acquired with the pulse generator disconnected.



**Figure 8: Peak and Average Spectra with and without Pulse Generator Active**

In certain frequency bands, around 220 MHz, 350 MHz, 450 MHz, and 700 MHz, there is a difference in signal characteristics when the pulse generator is turned on, vs being turned off. The peak spectrum is increased in these areas, while the average remains low. In other bands, there is little to no discernable difference between peak and average spectra with the pulse generator active or not active.

The data allows to identify frequency bands where the UHF sensors are most sensitive. These frequency ranges differ between different types of sensors and geometries, and often are unknown prior to the measurement. Performing a sensitivity analysis allows to adjust measurement systems to ensure that measurements are performed in frequency ranges where the used sensors are most sensitive.

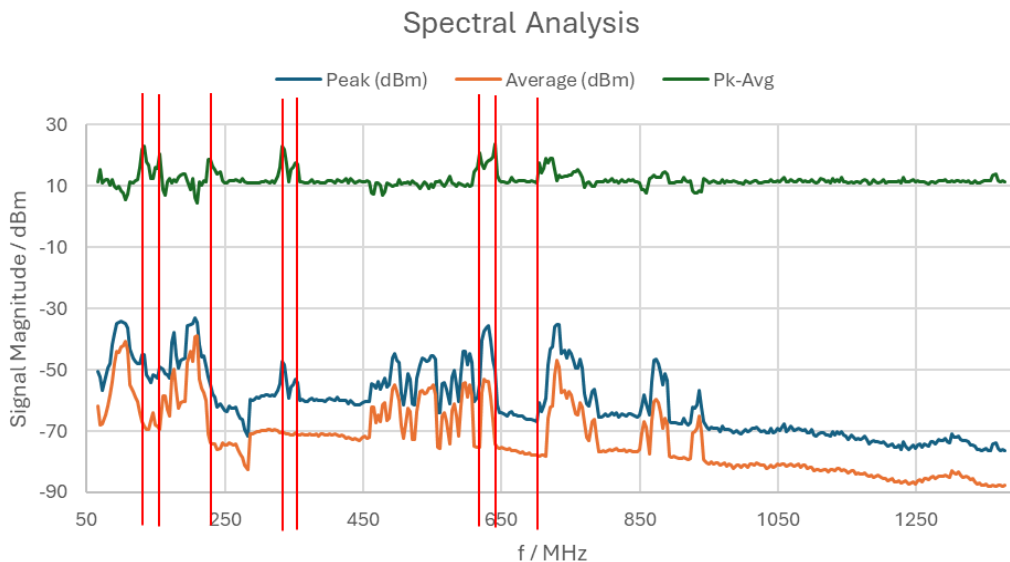
While the sensitivity check allows to determine suitable frequency bands for measurement, it requires multiple sensors to be available.

If a sensitivity check is not feasible, sensitive frequency bands of a UHF sensor may be determined as per the procedure described in the next section.

## AUTOMATIC NARROW-BAND TUNING AND PD DETECTION

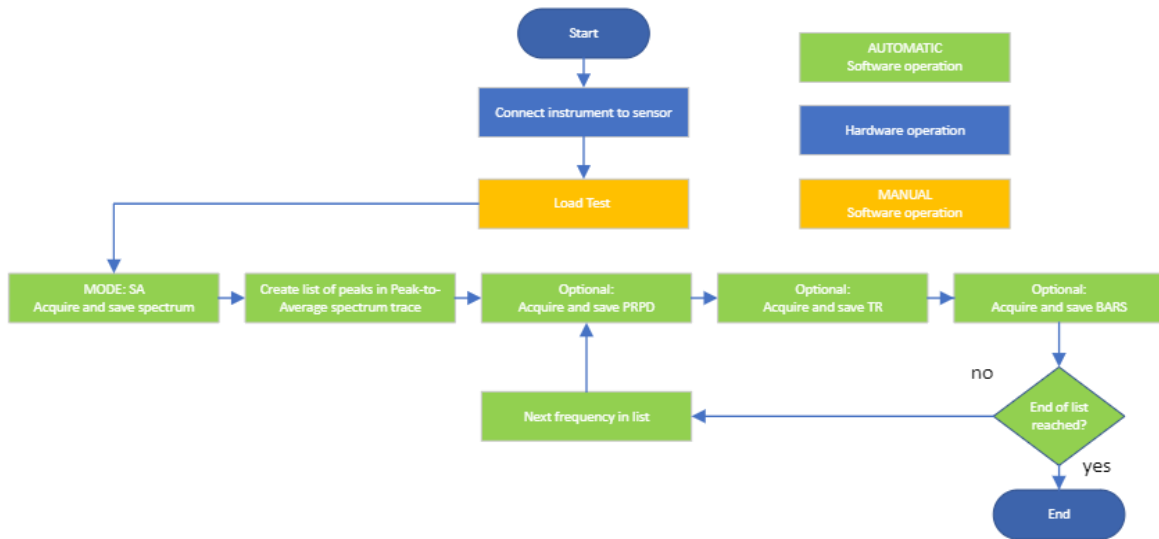
By analyzing the spectrum for local maxima in the peak-average ratio with suitable UHF detectors, frequencies of high sensitivity and presence of pulse shaped signals can be determined without a sensitivity check. This procedure can be done manually or automatically, reducing the need for subject matter expert operators and the overall complexity of the measurement.

Figure 9 shows a peak and average spectrum acquisition (blue and orange), as well as the value for peak minus average across the spectrum. Local maxima in that graph correspond to frequencies in which most likely pulse shaped signals are present, as the difference between peak and average is larger than in other frequency ranges. These frequencies are marked by red vertical markers.



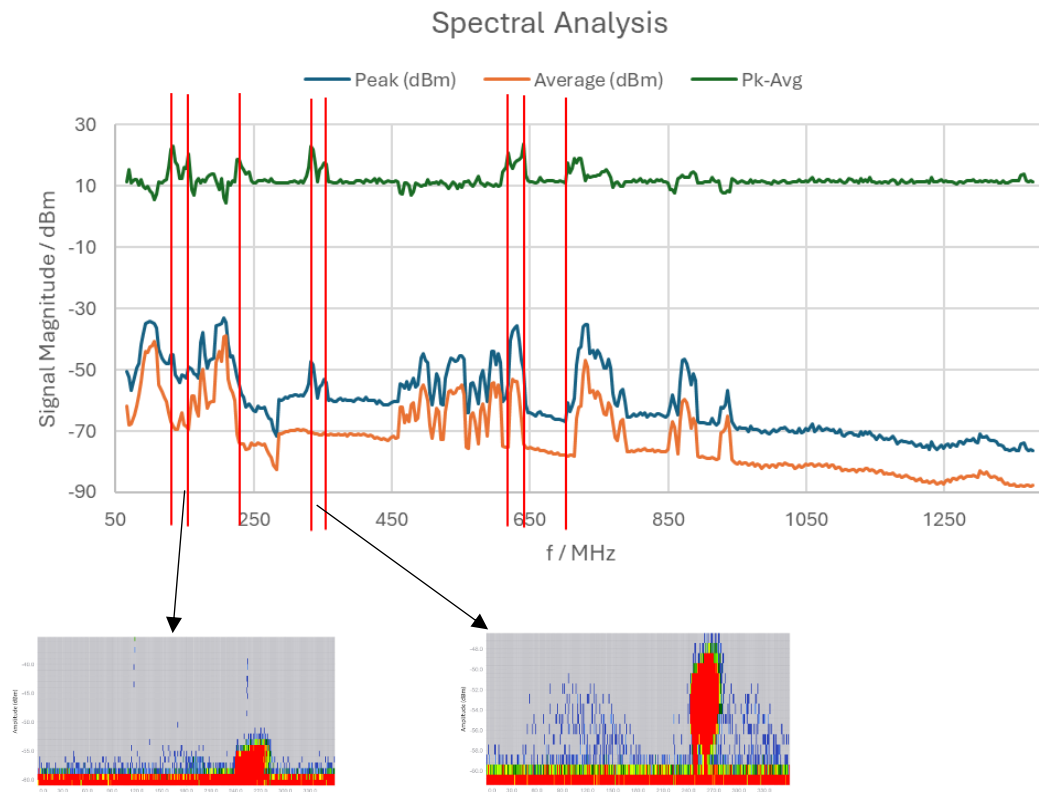
**Figure 9: UHF Spectrum with Identified Peak-Average Maxima**

In an automatic measurement, the measurement system then tunes to these frequencies and acquires relevant data automatically. The procedure is laid out in Figure 10.



**Figure 10: Automatic Narrowband Acquisition**

For the measurement above, the narrowband PRPD analyzed signals for two of the identified frequencies are shown in Figure 11.



**Figure 11: Narrow Band PRPD Analysis at Identified Frequencies**

For an automatic procedure such as the one described above, the only required manual measurement steps are limited to making the connection to the test object and starting the measurement. This procedure, done either manually or automatically, enables users to perform UHF PD measurements with significantly increased sensitivity in the presence of noise.

When a peak to average spectrum analysis can be performed, prior knowledge of the systems frequency characteristics is not necessary, and a sensitivity check is not required to determine sensitive measurement frequencies. Nevertheless, a sensitivity check is recommended, not only to check the sensitivity of the measuring system, but in order to verify the correct functioning of the installed sensors and the measurement chain [1].

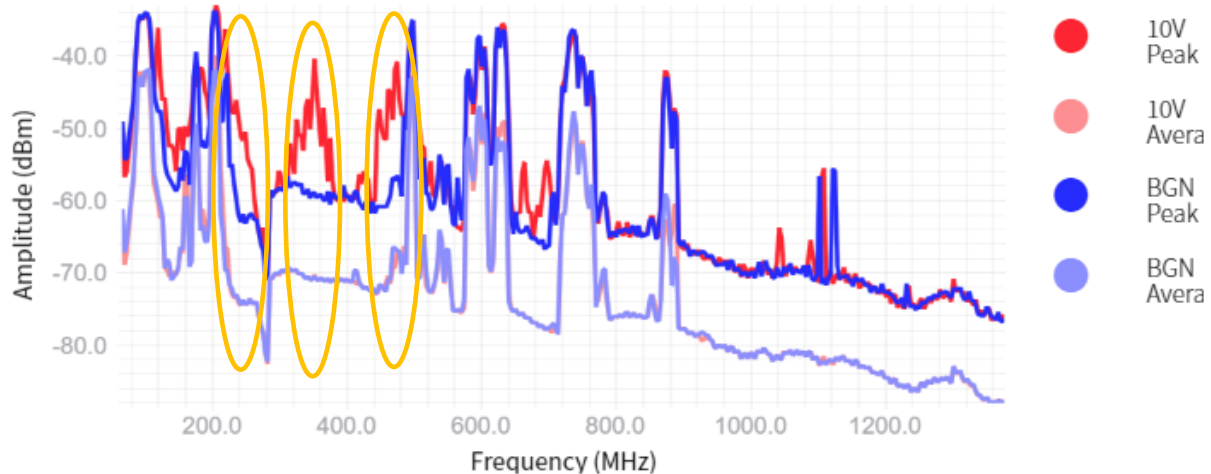
### CASE STUDY 1: 69 KV UHF GIS COMMISSIONING TEST WITH SENSITIVITY CHECK

This case study features data from a UHF PD commissioning test on a 69 kV gas insulated switchgear installation with internal UHF PD sensors.

The GIS featured approximately 90 internal UHF sensors, along with a monitoring system which connected to each sensor using a frequency shifter at the sensor. At the time of commissioning, the monitoring system was not operational. For the commissioning test, a narrow-band UHF measurement was mandated by the manufacturer. The frequency shifters were removed from the measurement sensors and the narrow band measurement system was connected temporarily to each of the detection points during the test.

Measurements were performed using a narrow-band UHF measurement system with spectral analysis features. A sensitivity check was part of the test procedure. The primary purpose of the sensitivity check was to ensure the proper operation of the installed sensors.

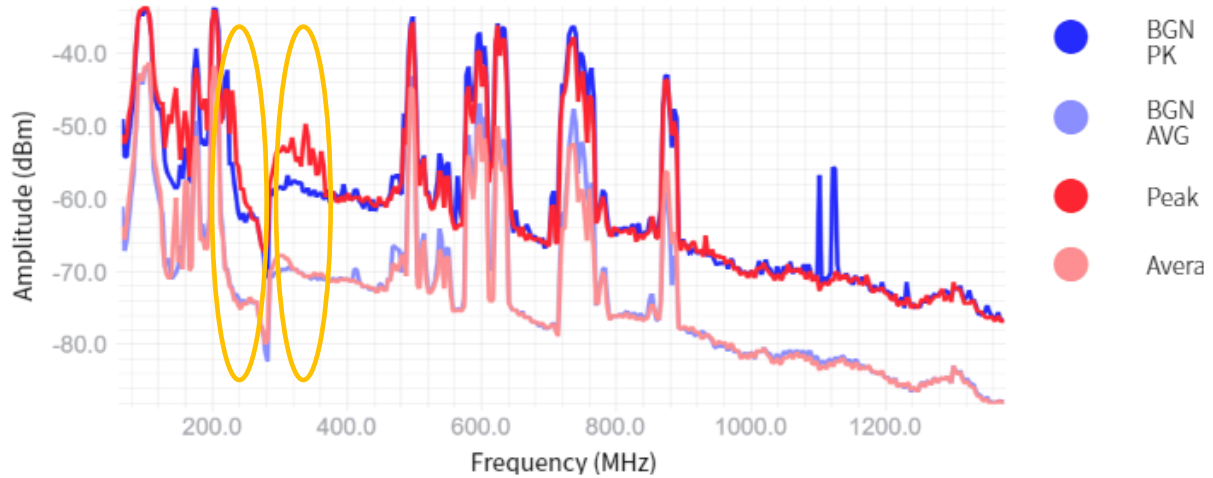
Figure 12 shows the peak and average spectra for the sensitivity check with the pulse generator on (red) and off (blue). Frequency ranges with high sensitivity of the measurement circuit are marked in orange. In addition to the identified bands of sensitivity, external nuisance signals of significant magnitude were observed around approx. 600 MHz, 700 MHz, and 900 MHz. Time resolved analysis at these frequencies showed modulated signals at specific carrier frequencies, at magnitudes that exceeded the observed sensitivity check and PD signal magnitudes.



**Figure 12: Sensitivity Test (Red: Pulses On - Blue: Pulses Off)**

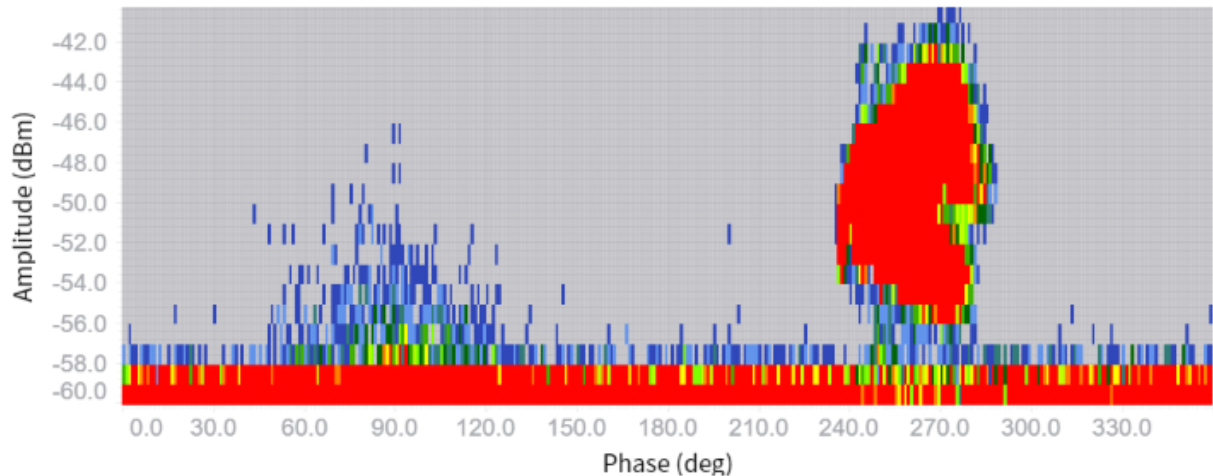
Subsequent to the sensitivity check, the device under test was energized using a resonance test system, and PD measurements were performed at a specified test voltage level. Figure 13 shows the spectra

acquired during the energization (red) vs de-energized (blue). Divergence between peak and average spectra is observed in frequencies above 200 MHz and around 350 MHz, marked in orange.



**Figure 13: PD Test Spectra**

Tuning to frequencies where pulse shaped signals were identified based on the spectral data, the phase resolved PD pattern shown in Figure 14 was recorded, showing signals indicative of void/surface discharge as well as corona.



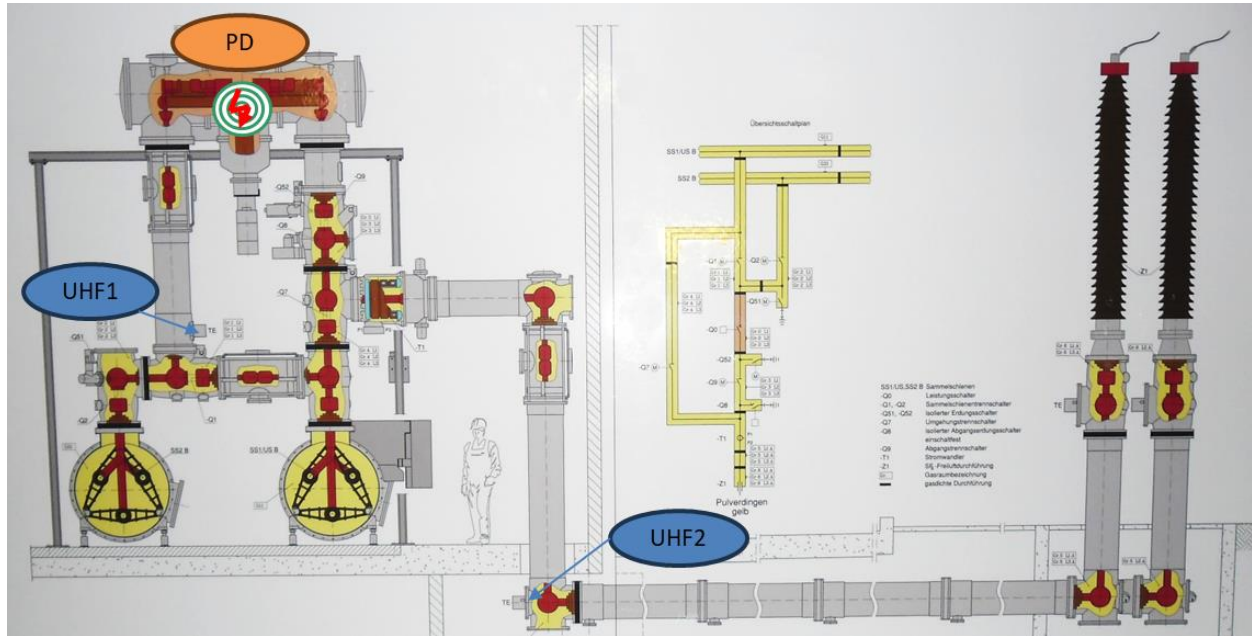
**Figure 14: PRPD Pattern at 219 MHz (6MHz BW)**

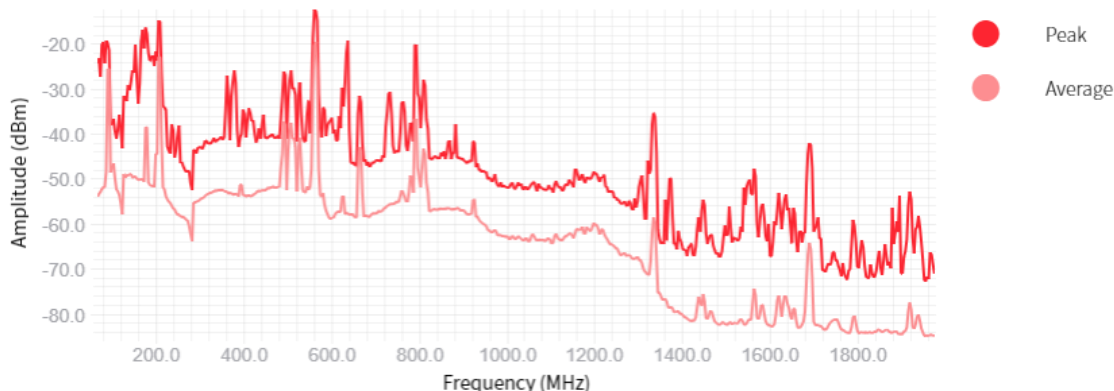
By tuning to these identified frequencies of interest with a limited bandwidth of 6 MHz, the system was capable of detecting and analyzing PD signals present in the device under test, without interference from nuisance signals present in the system, allowing for reliable detection of PD with increased sensitivity.

## CASE STUDY 2: 380KV GIS WITH KNOWN PD AND MULTIPLE DETECTION POINTS

This case study focuses on observations made during a UHF PD test on a 380 kV GIS with integrated UHF PD sensors. Measurements were performed using a narrow-band UHF in parallel with an Ultra-Wide-Band UHF-LF Converter measurement system.

The GIS under test had a known PD source in a circuit breaker compartment, and a measurement was requested to compare the results of a frequency conversion system to a narrow band system. The layout of the GIS, the location of the PD source and the two utilized PD sensors (“UHF 1” and “UHF 2”) is shown in Figure 15. For size reference, an engineer of approx. 180 cm height is depicted in the drawing.





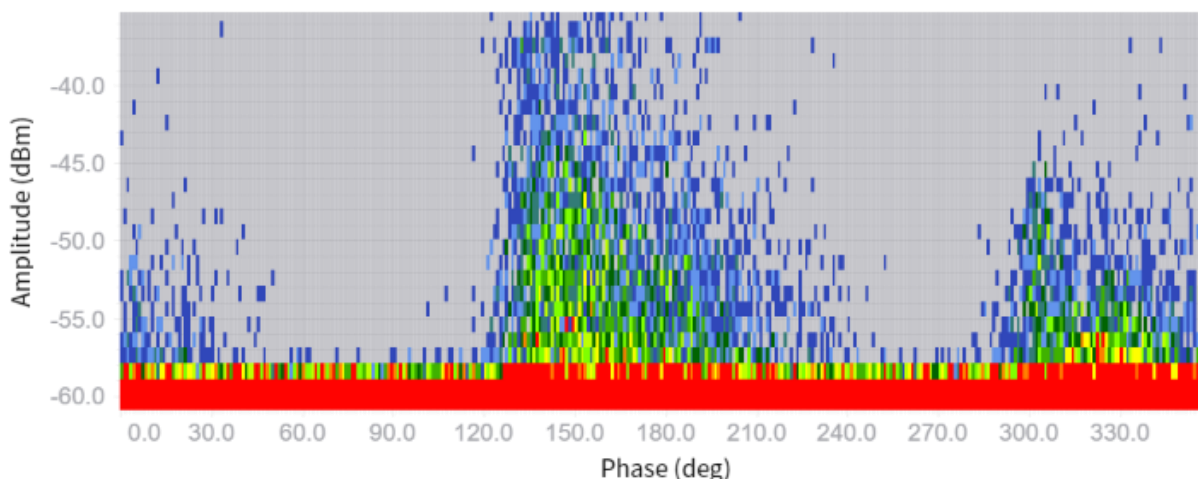
**Figure 17: Sensor UHF 2 Spectra (with +50dB Amp)**

The data on UHF 1, the sensor close to the PD source, in Figure 16, shows significant signal energy across the entire spectrum. The characteristics of peak vs average spectrum further indicate the presence of pulse shaped signals across the entire spectrum. As UHF signals are attenuated over distance, the signal characteristics indicate proximity to a PD source. Measurements done with wide-band UHF-to-LF conversion also showed clear PD patterns.

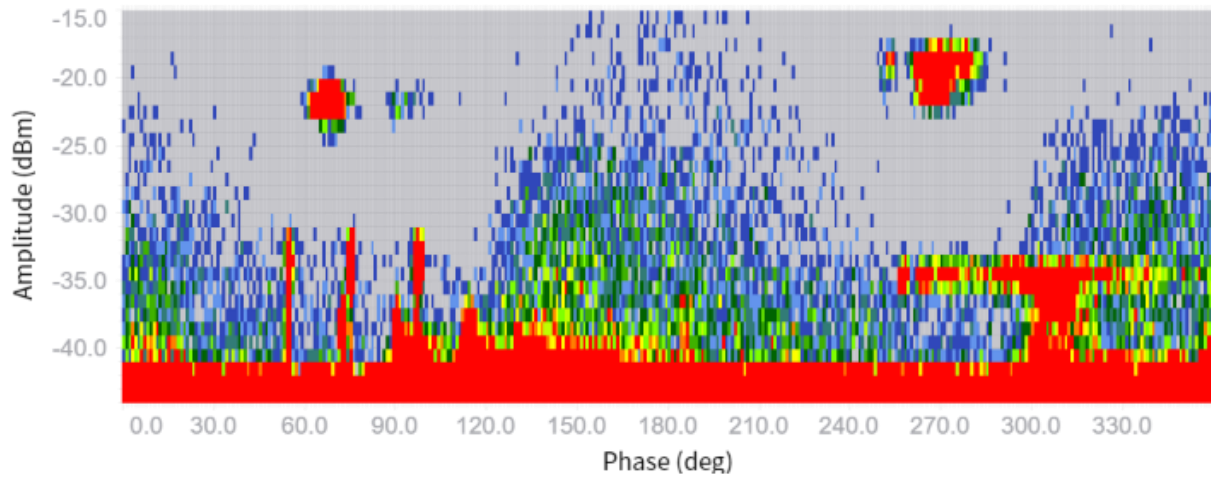
Signals measured on UHF 2, a sensor approximately 10-12 meters from the PD source, shown in Figure 17, exhibit significantly less signal energy across the spectrum compared to sensor UHF 1, due to the signal attenuation over distance. Furthermore, sensor UHF 2 shows frequencies in which the peak and average spectrum spike, indicating the presence of nuisance signals or noise. Measurements done with wide-band UHF-to-LF conversion did not exhibit any PD patterns on this sensor.

While PD signals were observed across the entire spectrum on sensor UHF 1, PD signals could only be observed below 200 MHz on sensor UHF 2.

The phase resolved PD patterns acquired at 185 MHz at sensors UHF 1 and UHF 2 are provided in Figure 18 and Figure 19. While sensor UHF 1 shows a clear PRPD pattern indicative of void or surface discharge across the entire frequency spectrum, sensor UHF 2 showed the same pattern only in a very limited band below 200 MHz. UHF 2 also shows signal characteristics of floating potential, contact noise, and corona, most likely from the GIS terminations connecting to the overhead lines.



**Figure 18: Sensor UHF 1 PRPD at 185MHz (with +30dB Amp)**



**Figure 19: Sensor UHF 2 PRPD at 185MHz (with +50dB Amp)**

The wide-band UHF to LF converted measurement conducted at the time of the assessment identified the void or surface discharge clearly on sensor UHF 1, but was unable to detect PD on sensor UHF 2, most likely due to the presence of nuisance signals in adjacent bands as well as the reduced signal energy across the spectrum in this measurement location.

The observations of the measurements are summarized in Table 1.

**Table 1: PD Measurement Observations**

Sensor	Signal Energy	PRPD Pattern	Narrow Band	UHF-LF conversion	Conclusion
<b>UHF 2 Far from source</b>	Low, 80 MHz-200 MHz, nuisance signals in nearby bands	Void/surface discharge, external contact noise and corona	detected	not detected	Sensor far from PD source (void/surface)
<b>UHF1 Close to source</b>	Significant, across spectrum	Void/surface discharge	detected	detected	Sensor close to PD source (void/surface)

## CONCLUSION

This paper presented two commonly used approaches to UHF PD measurements in frequency ranges up to 2 GHz.

While measurements utilizing lower frequency PD detectors via frequency conversion filtering provide a very easy and economical way of utilizing UHF sensors, in particular when a test object is equipped with a large number of UHF detection points, certain limitations in sensitivity are evident in the presence of UHF noise in the passband of the UHF filters. In applications with many UHF sensors this reduced sensitivity aspect is usually far outweighed by the economical factors as well and the availability of many detection points, but it may be a less favorable approach in applications where fewer detection points are available or where particular focus is laid on high sensitivity.

Narrow-band UHF measurements on the other hand typically require a significantly more expensive measurement circuit due to the potential need for expensive UHF amplifiers, and measurement procedures – requiring spectrum analysis and tuner adaptation – are more complex than using LF detectors with frequency conversion circuits. They are usually not deployed in applications that require frequent measurements on a lot of detection points, such as in permanent monitoring applications. However, ability to adaptively adjust the detector parameters to meet the measurement circuit characteristics as well as to avoid frequencies where noise is present from contributing to the measurement, provides a significant increase in sensitivity. Furthermore, by performing signal and transfer function analysis in the frequency domain, tuning to the narrow-band frequencies for phase resolved PD analysis is a process that can be automated based on parameters derived from spectrum measurements. Typical applications for using UHF narrow band measurements are hence focused on in-service condition assessments or commissioning tests of apparatus with UHF PD detection sensors.

Determination of the ideal measurement approach for a given application depends on a wide range of factors and requirements. Taking into account the requirements of a specific application and use case, be it monitoring or in-service testing, to determine a suitable measurement methodology, is key in ensuring an economical approach and reliable results. Both UHF-LF conversion and narrow band UHF measurement methods provide suitable and comprehensive tools to meet the diverse requirements of different applications as laid out in this paper.

Combining narrow band and spectral analysis as part of a sensitivity check in conjunction with frequency-converter based UHF-LF systems allows to make adjustments to the passbands of those circuits to ensure increased sensitivity during operation of such systems.

## REFERENCES

- [1] CIGRE, TB 654 - UHF partial discharge detection system for GIS: Application guide for sensitivity verification, Paris: CIGRE, 2016.

## BIOGRAPHIES



Falk Werner studied Electrical Engineering and Information Technology with a focus on Telecommunication and Signal Processing at the University of Stuttgart, Germany, where he obtained the academic degree "Diplom-Ingenieur" in 2009. His final thesis was entitled "Location of Partial Discharges by Means of Sensor Arrays.", focusing on Partial Discharge location in power transformers. Mr. Werner has in-depth knowledge of partial discharge (PD) diagnostics and measurement methods on high voltage insulation systems. At Doble Lemke he co-developed the PD solutions range. Mr. Werner has several publications to his credit.

He currently holds the position of Solutions Director for Partial Discharge and EMI at Doble Engineering Company, with previous positions as Solutions Manager, Principal Engineer and Senior Field Engineer, focusing on partial discharge, diagnostics, consulting, and solutions development. Mr. Werner is a member of and active contributor to IEEE, focused on the subject of partial discharge measurements and diagnostics. In over 15 years of professional experience in the field of PD, he gathered extensive R&D, field testing, and consulting experience in over 25 countries.



Philipp Wenger received the M.Sc. in electrical engineering and information technology from the University of Stuttgart, Germany in 2017. After his graduation, he was an Academic Researcher at the Institute for Energy Transmission and High Voltage Technology, University of Stuttgart. He was working in the field of gas-insulated switchgear (GIS), determining partial discharge activities under AC and DC voltage stress. Since 2022, he has been a member of the primary equipment team of TransnetBW. As a GIS technology expert, he is the central contact for technology-specific questions in the area of gas-insulated switchgear in all project phases and supports system operation with regard to

condition monitoring, maintenance and renewal strategies. He is involved in the technology development of GIS systems. He is an active member of the German Power Engineering Society VDE-ETG and Cigré.

## [KEYWORDS]

Partial Discharge, GIS, UHF, Switchgear