Limitations of Attempting Calibration of Partial Discharge Measurements in VHF and UHF Ranges

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Abstract- **There is an obvious desire to assign units of charge (pC) to on-site/on-line partial discharge (PD) measurements made using radio-frequency (RF) techniques by employing some means of calibration in a way similar to that defined in IEC 60270. While moving just a few MHz past the IEC 60270 mandated maximum cut-off frequency (1 MHz) may still allow the principle of quasi-integration to hold, and thus allow a valid charge-based calibration, this is strongly dependent on the test object and test circuit. However, at higher (RF/VHF/UHF) frequency regions in which PD diagnostics are often being made today on GIS and HV transformers, physical effects profoundly affect the RF signal generated at the PD source and its path to the receiving sensor, thus directly impacting the received RF signal strength. We explain the problems inherent in attempting charge calibration at these higher frequencies by looking at the fundamental difference in how the measurement methods acquire the PD signal, and we point out the relative unimportance of charge level for certain critical defects.**

I. Introduction

HV assets such as power transformers and gas-insulated substations (GIS) are designed to be as free of partial discharge (PD) defects as possible. PD-measurement has become the standard means for non-destructive testing of high voltage equipment insulation to detect and remove critical defects before they lead to insulation breakdown. Conventional PD measurements in units of charge (pC) were developed for laboratory work and for factory acceptance testing, becoming standardized as in e.g. IEC 60270 [1]. However, various factors combine to make these techniques difficult to employ on-site. Starting in the 1980s, radio-frequency techniques - often termed the 'UHF method' - began to be applied for on-site testing of GIS [2-5]. Detection sensitivities equivalent to the standardized lab and factory methods was achieved, with the added advantage of rejecting external interference (EMI); eventually these gained enough acceptance to negate the need for complex and time-consuming on-site lightning impulse testing. Based on their wide-spread application and acceptance on GIS (also for on-line monitoring systems), the UHF method also began to be applied to HV transformers [6].

II. Conventional, Charge-Based PD Measurement

Beginning in the 1960s, methodologies affording high enough sensitivity to detect harmful PD defects in HV equipment insulation had converged, including an agreed-upon means to calibrate the measurements in units of charge, subsequently becoming standardized [7]. Particular emphasis was placed on defining the calibration method and the response of the measurement circuit to PD signals from the equipment under test (EUT); this allowed defining equipment acceptance criteria in terms of charge (pC).

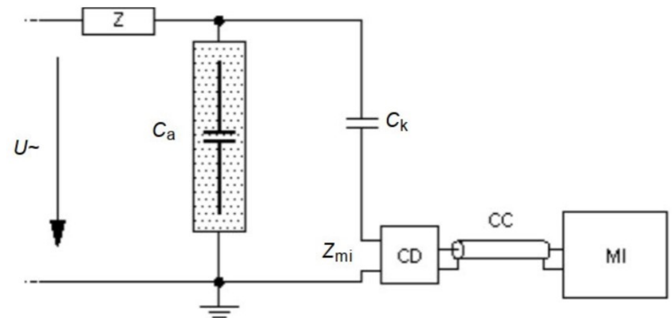

Fig. 1. Basic PD measurement circuit specified in IEC 60270 [1]

The well-known basic PD measurement circuit as defined in IEC 60270 [1, 7] is shown in Fig. 1, consisting of a variable high-voltage supply ('U'), an isolation impedance Z, and the equipment under test ('EUT', 'C_a') connected in parallel to the series combination of a coupling-capacitor ('C_k') and measurement impedance ('Z_{mi}'). Partial discharges in the EUT (C_a) result in displacement currents passing through the coupling capacitor and measurement impedance, the voltage across which is the measured signal. Because the EUT is galvanically connected to C_k and Z_{mi}, the output voltage from Z_{mi} is directly proportional to the current I_{PD} (not shown) flowing through the terminals of the EUT (C_a); this voltage is defined in units of charge (pC), based on the injecting a known level of charge directly into the measurement circuit as defined in the standard (Figs. 4a and 4b of [1]). However, as emphatically stated in [1], the charge so measured is the 'apparent charge', since the PD signal measured at the *terminals* of C_a is dependent on the precise capacitive relationship to the discharge site, which is generally unknown (outside of carefully controlled, purpose-designed laboratory set-ups).

Two fundamentally important facts must be emphasized for the purposes of this discussion: First, the output measurement

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signal is obtained from a circuit in which the EUT is directly (galvanically) connected, i.e. it has a direct relationship to the PD within the test object. Second, for measurement in units of charge to be valid, it is assumed that this output measurement voltage is proportional to the PD charge, i.e. I_{PD} is the integral of the PD pulses at the terminals of the EUT, referred to as quasi-integration [1]. However, for this principle to be valid, it is assumed that the spectra of the PD pulses from the EUT and from the charge calibration device contain the complete information concerning their time integral (charge, q). These assumptions only hold across a constant part of the spectrum and at relatively low frequencies (< 1 MHz) [1].

The upper limit of the constant part of the calibrated PD measurement spectrum depends on the rise time of both the PD signal and the calibrator, and is thus limited by the frequency-dependent signal transmission path between the actual location of the PD source within the EUT and its terminals, the dimensions of the EUT, and its connections to the measurement circuit. Simple, compact test objects such as GIS exhibit a flat spectrum even exceeding the limits given in [1] (< 1 MHz); however, EUTs with significant inductance or dispersion, such as transformer (or rotating machine) windings (and e.g. HV cable) reduce the upper frequency limit at which quasi-integration holds as valid, especially for defects located deep within such structures [10]. Indeed, these effects are touched on in IEC 60270; when attempting to measure PD at higher frequencies, extreme caution must be observed when assuming units of charge are valid for the signals measured.

II. NON-CONVENTIONAL PD MEASUREMENTS AT RF FREQUENCIES ('UHF-METHOD')

For the reasons already mentioned, the UHF method began to be applied to detecting PD in GIS starting in the 1980s [2-4].
In this context, the most important conceptual points are: 1) we use a sensor to pick up the RF signal 'broadcast' by the PD defect, at some (unknown) distance and without (galvanic) connection to the defect, 2) therefore the signal received is dependent on the actual RF output signal from the PD source, the complex, frequency-dependent transfer function along the propagation path, and the frequency-response of the sensor, 3) the complex transfer function along the signal path is location dependent, 4) the location of the PD source is unknown, and 5) different PD defects produce different RF signal level relative to their actual (pC) charge [5, 8]. An attempt to diagram this unhappy situation is shown in Figure 2, and a sample RF transfer function (frequency response) from an actual sensor-sensor path on a real GIS is shown in Figure 3. The frequency range (x-axis) is from 0 - 2 GHz and the major divisions (y-axis) are 20 dB apart. Besides the sharp peaks and valleys, the broad and deep rectangular notch in the spectrum is remarkable. Note that making the same transmission measurement just on an adjacent phase will almost always result in significant changes to the plotted spectrum. Lastly, Figure 4 shows two PRPD patterns of the same defect taken at two different sensors: obviously the received RF signal amplitude has nothing to do with the defect's actual charge.

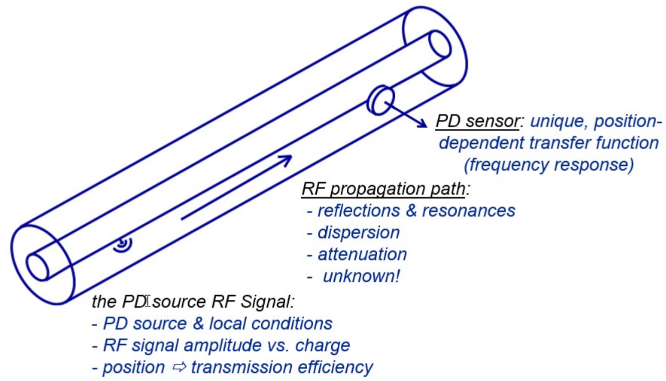

Figure 2: PD RF source, the RF propagation path, and the receiving sensor

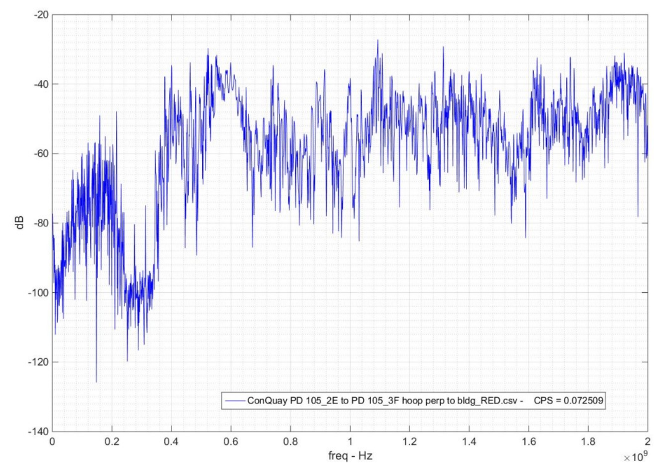

Figure 3: RF frequency response through a U-shaped section of GIS [9]

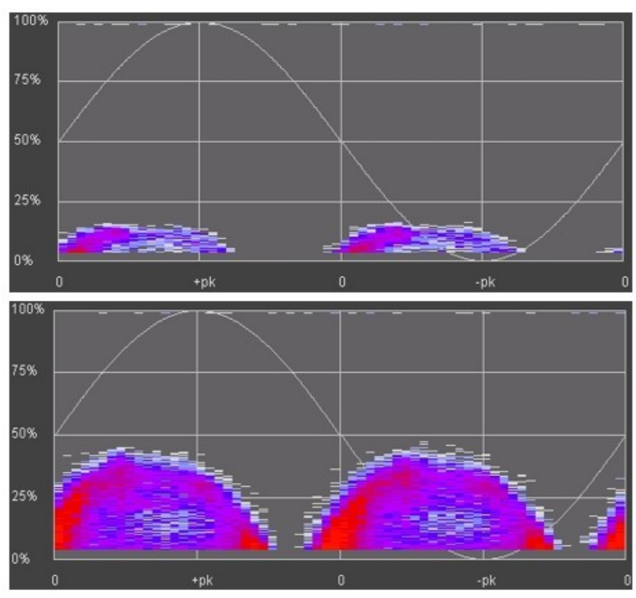

Figure 4: PRPD patterns of the same defect at two different UHF PD sensors

Although at first glance GIS appears to present the well-behaved RF transmission environment of a coaxial waveguide, two important factors prohibit that: the UHF wavelengths at which we are measuring are of the same order as the internal dimensions of the GIS, and the GIS itself is filled with abrupt impedance changes which result in powerful signal resonances and signal 'traps' [9, 10] - these are responsible for the very 'un-flat' frequency response spectra we see, typified by Fig. 3. Additionally, the currently accepted value for the rise-time of PD in SF6 is ~30 ps [11] translating to RF spectral components out to 15 GHz, a wavelength of 2 cm. This means our PD signal is exciting a multitude of higher-order modes within the GIS volume which interact with each other, making the RF signal 'broadcast' by the PD defect even more location-dependent. These effects are covered in [4, 9, 10] along with many of their respective reference citations as well.

These effects on received signal amplitude were known from the early days of UHF PD measurements, such that the GIS community agreed on the need to demonstrate RF techniques were capable of detecting harmful PD defects. The result was the so-called 'CIGRE Sensitivity Verification Procedure' ('CSVP') [12], a two-step method consisting of injecting a fast rise-time pulse into each PD sensor in the GIS, and observing if the signal is visible at the next sensor(s); the pulse generator output level is first set to match the UHF signal produced by a moving particle whose charge is 5 pC (calibrated in the IEC 60270 test circuit) in an initial defined factory test.

All of this is well-understood and has been proven over 20 years' experience and is now accepted practice [12-14]. The problem arises when the CSVP is confused with 'calibration' as defined in IEC 60270 [1]. They are not the same, for the following reasons: 1) in IEC 60270, we inject a known charge directly into the measurement circuit in which the terminals of the EUT are galvanically connected, while when preforming the CSVP, a pulse generator signal is 'broadcast' from a PD sensor, which leads to the next point 2) exciting a PD sensor with a pulse generator is a totally different physical process from a tiny micro-spark producing a fast RF pulse at an unknown location somewhere within the GIS. Again recalling from above: since the exact location of the PD defect is unknown, we cannot know exactly how its RF signal will be 'broadcast' and, since we cannot know the exact RF transfer function from that unknown location, we cannot make any valid assumptions about the signal that arrives at the sensor. In other words, from the perspective of a defect located somewhere between 2 PD sensors, we cannot assume a flat-line attenuation profile between them, of x dB per unit distance y, for the purpose of attempting to estimate charge.

Perhaps a simple thought experiment can illustrate this point. Imagine a long dark corridor with rooms off both sides. Holding a candle (the signal source) at either end of the corridor, an observer at the opposite end will note the intensity of the candle. As we move toward or away from the observer, or if we light two or three candles, the observer will be able to estimate something about the distance to the candle(s) based on the apparent brightness (received signal strength). However, if we just duck into the doorway of one of the rooms off the corridor, the observers on either end of the corridor will only have whatever reflected light is available to estimate where the candle is or how many there are. The analogy is not perfect, but the doorways off our corridor represent local departures from an assumed flat linear attenuation profile. We do not know in which doorway the candle is or if it's a big candle or a small candle - we don't know from which wall its light is being reflected or even if the wall is painted a dark color. The variability of GIS signal propagation leads to strange effects; the authors have first-hand experience of UHF monitoring systems displaying higher signal amplitudes from overhead line noise (corona) on sensors further inside the GIS building instead of the sensors nearer to the outdoor bushings.

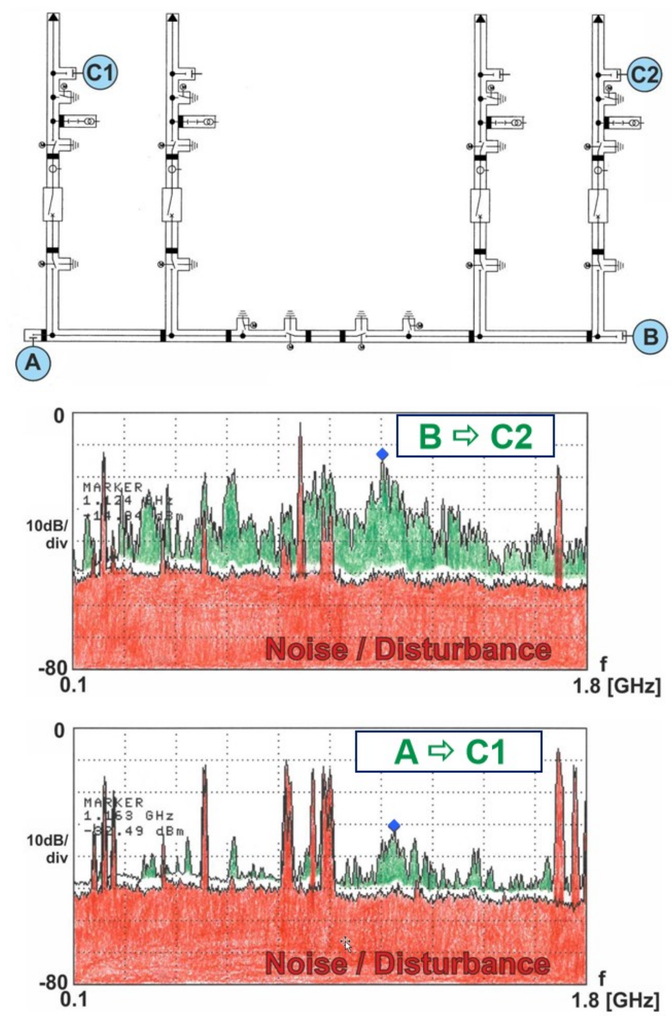

Figure 5: Effect of slight difference in sensor position on path propagation

Figure 5 shows an extreme example of the dependency of the RF propagation path transfer function on even minor changes in geometry. The signals received on an RF spectrum analyzer are shown while carrying out the CIGRE sensitivity check on two different GIS paths; although the sections are almost identical, the obvious large difference in signal amplitude is due only to slightly different mounting position of the pulse input ('transmit') sensors. Sensor A was mounted on a side flange at the end of the busbar, while sensor B was installed in the center of the end cover-plate of the busbar. Besides this minor difference (plus one additional spacer between A & C1), the sensor type as well as the GIS configuration along the two paths were the same. Although there is <5 % difference in the path lengths, the signal strength differs by approximately 17 dB (50:1) when measured at the same peak, and the overall difference in the total energy in the spectrum is obvious even in the small plots shown.

Another point of confusion arising from the desire to attempt signal strength calibration is the trend toward 'calibrating' UHF PD sensors as if they were antennae, e.g. in terms of equivalent height (i.e. referenced in terms of the height of a monopole above an infinite ground-plane). Work has centered on using GTEM cells for this purpose [15, 16] by installing the candidate sensor in the upper horizontal 'ceiling' of the GTEM cell. The PD sensor output is recorded while an RF source connected to the GTEM cell input is swept across the desired frequency range, or a fast impulse is fed into the input and the FFT of the sensor output taken.

This methodology suggests a sound basis for qualifying PD sensors in terms of sensitivity, and some utilities even began specifying it to qualify sensors [17], though it was later withdrawn upon arrival of the CSVP [18]. However, there are several problems using GTEM cells in this context. First, these sensors are not technically 'antenna', a term which, in the world of antenna engineering and electromagnetics, refers to a radiating (or receiving) apparatus acting in its 'far field', typically taken to be >10 wavelengths distant from its center point [19]. However, even at the upper limit of the UHF band (3 GHz) in *1100 kV* GIS, the distance between the PD sensor and the center conductor is just a few wavelengths; even at 300 MHz, within about half a wavelength. This means UHF PD sensors are acting in their extreme near field. Next, we recall the existence of higher-order modes and the overall RF propagation environment inside the GIS, whose internal dimensions are of the same order as our measurement bandwidths [9, 10]; this means the PD sensor's exact position relative to neighboring surfaces - both conductors and insulators - will have profound effects on its RF behavior. On the other hand, GTEM cells were specifically invented to test components in a defined uniform electric field within the test volume, indeed, they are purpose-built to prevent higher-order modes [20]. Meanwhile, UHF PD sensors live in an RF environment which inherently exhibits *at best* a radial electric field (true only at the low end of the spectrum) plus multitudes of complex modes, totally different from the uniform/normal and homogeneous electric field within a GTEM cell. A UHF sensor is an intimate part of the GIS' internal design. That means a perfectly sensitive, well-behaved sensor in one OEM's GIS will not only not fit into the GIS from another OEM but may also perform very poorly. Assessing the RF performance of a GIS PD sensor inside a GTEM cell is simply not a valid test of how it will perform inside 'its own' GIS (the same reasoning applies to UHF sensors inside HV transformers - their actual near-field RF environment is nothing like what the sensor 'sees' inside a GTEM cell).

III. Signal Amplitude vs. Criticality

The emitted RF signal energy vs. IEC 60270 calibrated apparent charge differs by more than an order of magnitude for different PD defects [5]. This means certain defects require higher UHF measurement sensitivity to detect, despite them showing similar IEC 60270 apparent charge levels. To illustrate this difference in relative RF signal output, the RF signals of three different fault types are shown in Fig. 6 for the 0.1 – 1.8 GHz frequency range. These spectra were acquired (3 minutes, 'MAX HOLD') during on-site commissioning tests via internal UHF-PD sensors and wideband UHF preamps.

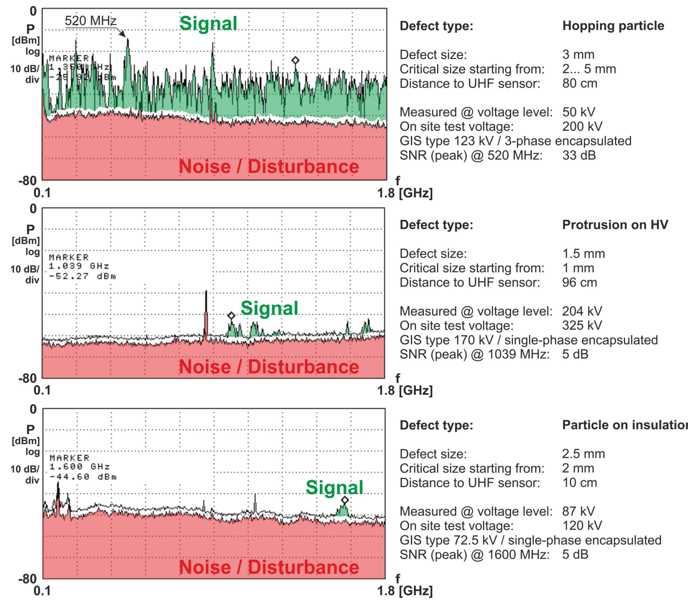

Figure 6: RF spectra of 3 different PD fault types, measured on site; resolution bandwidth 3 MHz; critical defects referenced [21]; 50-dB preamplifier [8].

Whereas hopping particles produce a strong broadband signal, Fig. 6 shows measurements of critical defects e.g. a particle laying on insulation or a protrusion on the GIS inner conductor which generate much lower RF signal strength and lower *apparent* bandwidths, because only the highest peaks get through the GIS' complex filter function and rise above the noise floor. The criteria for determining the critical defect size which could potentially cause a flashover in service, e.g. for ‘protrusion on HV’ and ‘particle on insulation’, is defined in terms of their reduction of the lightning impulse withstand capability [21]. The signals shown in Fig. 6 were from defects close to the minimum critical size. Such defects will likely pass the one-minute AC high voltage test undetected (due to 'corona stabilization' [22]) but can fail the lightning impulse test; for example, a protrusion on the HV conductor may pass the full-rated AC withstand voltage but flash over at 30% of the lightning impulse withstand voltage (LIWV) [23], and a 2 mm particle laying on an insulator surface can reduce LIWV by up to 50% [24]. Such defects in GIS could possibly flash over as a result of transient voltage stress. Whereas defect types like hopping particles or floating parts are easily detectable with a UHF PD measurement at nominal operating voltage, particles on insulation or protrusions on HV live parts can usually only be detected with a very sensitive UHF PD measurement at increased test voltage [21].

A difference in signal-to-noise ratio (SNR) between the ‘hopping particle’ and the ‘particle on insulation’ of more than an order of magnitude is clearly evident in Figure 6. Also, the apparent charge levels of such minimum critical defect sizes (‘protrusion on HV’: 1 mm length, 1 - 2 pC, ‘particle on solid insulation': 2 mm, ~0.5 pC) are very low when measured at 80% of the AC withstand voltage; such levels of IEC 60270 detection sensitivity and SNR performance are usually impossible to approach, given the high-level interference environments typically encountered on site.

IV. Concluding Remarks

We have discussed detection and measurement of PD defects using RF techniques (the 'UHF method'), differentiating those methods from conventional, charge-based PD measurement as defined by IEC 60270 [1], with particular emphasis on charge calibration. In IEC 60270, the direct connection of the EUT within the measurement circuit together with the charge injection calibrator afford a realistic confidence level of the measured apparent charge value, but no analogous case can be made for assessing defect charge using RF-based ('non-conventional') methods. The combination of not knowing the exact type or location of the PD defect (and thus its RF signal 'broadcast efficiency') or the actual RF transfer function along *that* specific signal propagation path (to the PD sensor) fundamentally prohibits assessing defect charge based on the received RF signal strength. Knowledge of the sensor-to-sensor RF transfer functions (RF signal attenuation profile) based on results of the CIGRE CSVP Step 2 test only apply to those specific individual measurement results and thus cannot mitigate this problem. Applying more rigorous methods to determine PD sensor sensitivity (e.g. GTEM cell tests) as part of a general RF 'calibration' are fruitless because such methods cannot represent the actual RF performance of the UHF sensor in situ within the GIS (or HV transformer); moreover, the exact defect-sensor propagation path still remains unknown. Finally, we explain that attempting to assess charge based on received RF signal strength is anyway of limited use, citing certain PD defects whose relative RF energy output is low, but which can pose a risk under transient voltage conditions.

Based on the above, instead of attempting to obtain a questionable estimate of a defect's charge value (pC) from an RF signal, it is better to focus effort on obtaining the highest sensitivity (SNR) possible, by careful design and placement of RF (UHF) sensors along with the accompanying electronics. This will improve defect detection and identification (through enabling clearer PRPD patterns), as well as aiding location accuracy (i.e. when employing arrival-time techniques). Especially on site, estimating a defect's actual charge value is not so crucial; but rather its detection, identification, and location are more important.

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