Procedures to Qualify PD Measuring Instruments to use in the Insulation Condition of Cable Systems

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ABSTRACT

Insulation condition of equipment and materials installed in HVAC and HVDC grids is evaluated using online PD measurements by means of PD analysers operating in the HF range (< 30 MHz). To achieve homogenous and comparable results during on line measurements, calibration of PD quantities and characterization of built in diagnostic tools of PD analysers according to standardized procedures are needed. This paper presents procedures to qualify PD measuring instruments used for insulation condition.

KEYWORDS

Partial Discharges, Characterization of PD instruments, Type discharges, HFCT sensor, Electrical noise, Electrical insulation diagnosis.

INTRODUCTION

Nowadays, on line Partial Discharge measurement is one of the most important diagnosis methods [1] and [2] for predictive maintenance of the high voltage cable systems.

Different no conventional PD electromagnetic methods operating on the high frequency range (up to 30 MHz) are used, however, few technical requirements are defined for this kind of PD instruments [3]. For this reason, a European Project in the Metrologic Research Programme (EMPIR) was approved in 2016 to develop a procedure to qualify the capabilities of PD instruments working in HF range in order to check their performances [4].

The proposed qualification method consists in generating trains of reference PD pulses from controlled test cells in a specific voltage range. The controlled PD pulses from different test cells are saved and later they can be mixed with different types of noises (modulated noise, communication PLC noise, random noise, electronic noise, etc.) in order to check the sensitivity in PD detection under representative noise operation conditions.

Different types of representative discharges can be simultaneously generated: cavity defect, surface defect, corona effect and floating potential discharges to analyse the PD instrument capability to discriminate them.

In addition, the test configuration allows analysing the capacity of the PD measuring instrument to discriminate where a PD source is located when it is close to two different high voltage elements.

This paper presents the portable testing setup developed to be used to determine transfer function of HFCT sensors, the scale factor k_q (pC/mV) for specific PD pulse waveforms, the ability to discriminate different PD sources, the capability to the location of a PD source by polarity recognition.

HFCT SENSOR CHARACTERIZATION

High frequency sensors are commonly used for the PD measurements in high voltage grids. It is interesting to determine the transfer impedance of the HFCT sensors expressed in Ω (mV/mA), as well as the phase shift introduced by the HFCT sensor expressed in electric grades. In this way, the amplitude of the signal and the distortion of the current pulse measured by the PD instrument can be estimated. A testing setup has been developed, consisting of a variable frequency generator, a shielded cylindrical compartment, in which the HFCT sensor is placed and connected to a digital oscilloscope through a coaxial cable of 50 Ω. The measurement of the injected current signal, I_{in}, is transformed into a voltage signal, V_{in}, by circulating the current through the load impedance (Z_{load}) of 50 Ω arranged on the oscilloscope terminals (Channel 1). The oscilloscope is used in high input impedance mode, 1 MΩ, so that a voltage V_{in} proportional to the injected current I_{in} (V_{in} = 50 I_{in}) is measured. The output signal of HFCT, V_{out}, is sent to the Channel 2 of the oscilloscope.

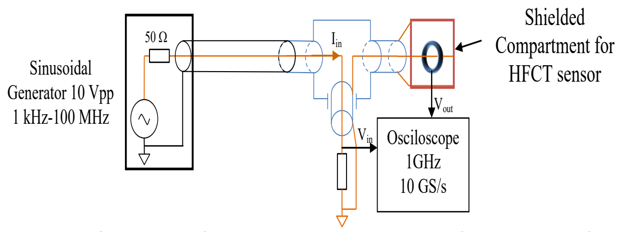


Fig. 1: Circuit of the measuring configuration for determining transfer impedance of an HFCT.

The frequency generator generates sinusoidal waves of frequencies ranging from 0.1 kHz to 100 MHz and the oscilloscope with a bandwidth of 1 GHz, 10 Giga-S/s collects the signals generated by scanning the frequency range. For each discrete point in frequency in which the transfer impedance of the HFCT sensor is measured a sufficiently large number of readings are performed, in order to reduce the random noise component.

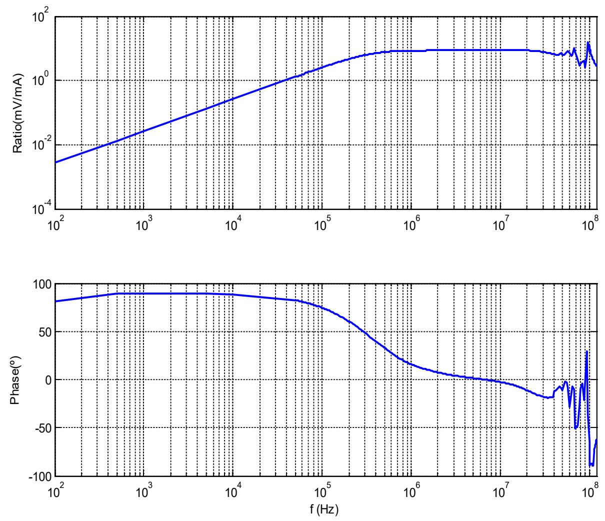


Fig. 2: Measurement result of the transfer impedance of a commercial HFCT: Gain and angle shift.

Figure 2 shows the transfer impedance: gain and phase angle curves of an HFCT sensor as a function of the frequency in a measurement range between 0.4 MHz and 20 MHz.

Figure 2 shows three different behaviours of the sensor, for frequencies below about 200 kHz the sensor behaves as an inductance with the transfer impedance (V_{out}/I_{in}) proportional to the frequency and with a phase shift of approximately 90°. From approximately 1 MHz to around 20 MHz, the behaviour of the sensor is like a constant impedance (sensor gain V_{out}/I_{in}) approximately 8.8 Ω. For frequencies above 60 MHz, the sensor has significant resonances.

The measuring cable affects the frequency response of the HFCT sensors very sensitively, especially in the phase shift, which can lead to a significant distortion of the recorded pulse waveform. Figure 3 shows the result of the frequency response of a sensor of another commercial HFCT type sensor with transfer impedance of 4.4 Ω in the high frequency range, for different cable lengths between 0 m to 15 m. It can be seen that although gain does not change significantly, the angle error does so for frequencies above 200 kHz.

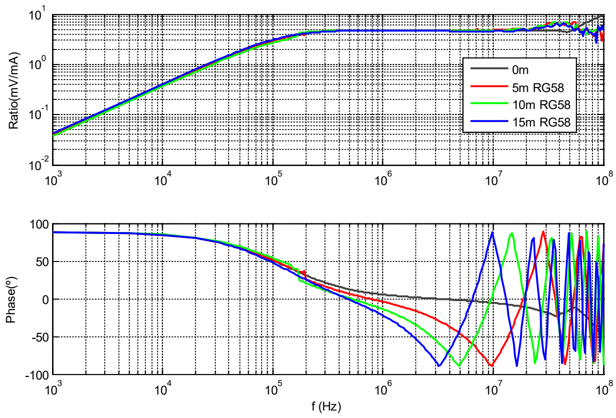


Fig. 3: Transfer impedance versus cable length of its coaxial cable.

CHARACTERIZATION SETUP

<u>Testing Setup description</u>

The important objective of this testing setup is to record trains of reference PD pulses so that they can subsequently be reproduced in a controlled manner as high frequency signals to be measured by the diagnostic analyser under characterization. To this end, a 200 MS/s digital recorder connected to a PC is used, that is capable of recording up to 5 minutes of PD pulse signals, as well as synchronization signals. The synchronization signals are used to correlate the measured magnitudes about PD activity: for example the output voltage of a PD pulse U_{xi}, and its starting instant (t_{xi}) with the measurements made by a reference measuring system: charge magnitude q_{si} (in pC), and the reference starting instant (t_{si}).

The testing configuration is composed of different modules (see Figure 4). The high voltage generation module G, capable of generating power frequency or direct voltages as desired, consisting of an AC generator of up to 15 kV r.m.s. value, which can operate in DC mode up to 30 kV. The output voltage is connected to the test configuration through a filter, F, to reduce the conducted noise. A high-voltage divider with a ratio of 10,000 is used to measure the applied voltage. The high voltage is applied to the PD Generator module, where PD test cells are available. This module has a coupling capacitor C_k of 1 nF to drain the generated PD pulses through the "HFCT PD measurement module". This last module consists of a shielded compartment, inside which a reference HFCT sensor is installed, by which the current pulse of the partial discharge generated is coupled to a measuring impedance through the reference HFCT sensor. The output of the HFCT sensor is carried to the channel #1 of the recorder controlled by a PC.

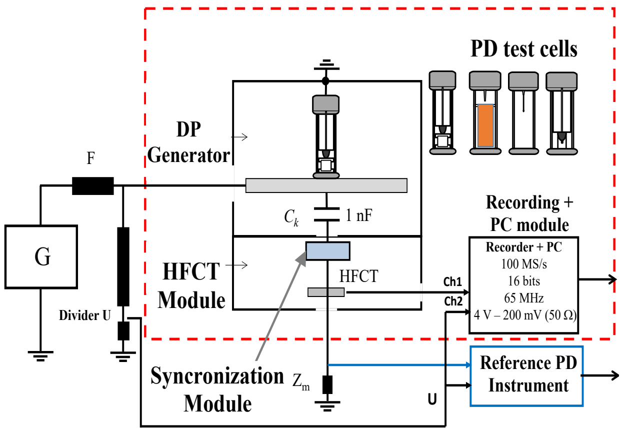


Fig. 4: Configuration of the system for the characterization of measurement systems and PD diagnostics.

The reference measuring impedance Z_m is connected in series with the coupling capacitor after the HFCT module and before grounding connection. In this way, the PD pulse will be measured by the two different sensors and measuring systems: the reference measuring system that uses the measuring impedance, Z_m, and a reference PD instrument and the other one constituted by the HFCT sensor and the "PD recording module" composed of a recorder controlled by a PC.

In order to synchronize both measurement systems: the reference and the “PD recording module”, another additional HFCT sensor is available just before the signal is coupled to the "HFCT measurement module", as shown in Figure 4. This HFCT sensor, works as a synchronization pulse injector, fed through by means an external synchronization pulse generator. A synchronization pulse of 2 µs duration and with an opposite polarity to the pulses of PD generated by the tests cells is injected every three seconds, approximately. These pulses are used to correct the time drift of the two clocks of both measuring systems.

Train of reference PD pulses

Four PD pulse test cells representative of type discharges have been developed: corona, surface discharges in the presence of ambient air, cavity defect in solid insulating material and floating potential discharges at metallic conductors, designed to generate stable pulses of PD as described in [5].

Every train of PD pulses are generated in the "pulse generation module" using only a certain type test cell as shown in figure 5. The train of PD pulses are generated when the test voltage is applied. Simultaneously they are recorded through two measurement systems (figure 4): the reference one and the own integrated in the test facility (HFCT sensor, with a digital recorder controlled by the PC). The saved train of PD pulses shall be later processed to recompose as accurately as possible their waveform in the range of frequencies between 1 MHz and 30 MHz where HF system to be calibrated operate.

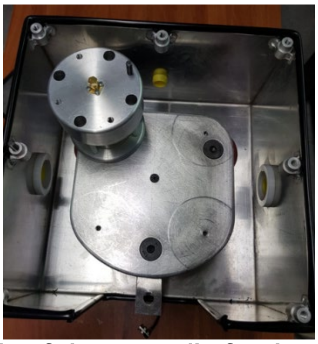


Fig. 5: Module of the test cells for the generation of trains of PD pulses waveforms.

The reference measurement system allows measuring the value of the reference charges q_{si} and instants t_{si} in which the PD pulses appear (see figure 6). The reference pulse starting times t_{si} will serve to search in the raw data saved by the digital recorder, the PD pulse waveform that originated the charge value q_{si} measured by the reference measurement system. To this end, a search is made of the transient event of greater amplitude that is in a range of times comprised between ±10 µs of the starting instant t_{si} measured by the reference system.

In practice, not all the pulses that the reference system considers as PD are really PD pulse signals, especially those of lower amplitude, due to electrical noise influence. It is necessary to remove the pulses that were identified as PD pulses by the reference measuring instrument and that after a thorough analysis of its waveform it can be ensured that they are electrical noise signals and not PD pulses. A tool was developed that allows analysing each pulse by two variables: its amplitude and its equivalent frequency. Table 1 shows the effectiveness of the method to distinguish the electric noise signals using this method.

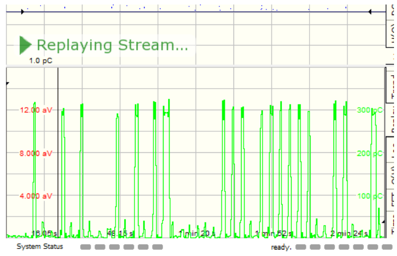
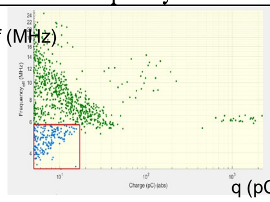
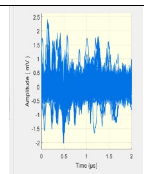
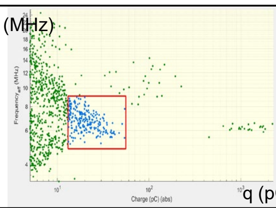
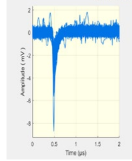


Fig. 6: Measurement of charge and instants of the DP pulses measured with the reference system

The pulses of low charge and low equivalent frequency have a high probability to be electric noise signals, while the pulses with big charge and big equivalent frequency have a high probability to be PD pulses. Pulses identified as electrical noise are removed in order to maintain only PD waveforms in the train of reference PD pulses.

Table 1: Numeric tool for removing noise signals mistakenly considered as PD.

Equivalent frequency versus charge	Waveform
 f (MHz) q (pC)	 Noise signal
 f (MHz) q (pC)	 PD pulse signals

Thanks to the application of this analysis tool, reference trains of PD pulses are achieved with only PD pulses, without electrical noise signals, as shown in figure 7:

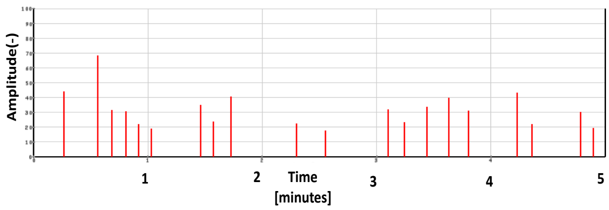


Fig. 7: Train of reference PD pulses after removing electrical noise signals.

QUALIFICATION PROCEDURES FOR PD INSTRUMENTS

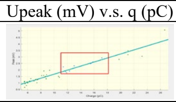
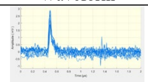
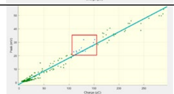
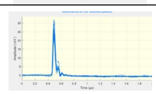
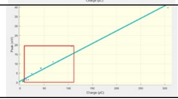
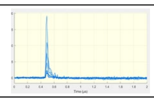
Analysis of the Scale Factor a measuring instrument

Scale factor is the value of the instrument reading is to be multiplied to obtain the value of the input quantity. For example, for a measuring system whose instrument reading is expressed in mV and its input signal is a current PD pulse of a known charge, the scale factor is expressed in pC/mV. However, this scale factor definition depends on the pulse waveform. For this reason, the scale factor can be only used to compare different measuring systems, but must not be used as a conversion factor for on-site measurements. For on-site PD measurements, even if the measured current pulse has the same waveform as the standard pulse, the charge evaluated by means of the scale factor is not the involved charge at the site of the discharge. The measured charge depends on the on-site parallel capacitances because an unknown part of the discharge flows through the high volt equipment and power grid. Apparent charge is not easy to be applied in online PD measurements.

Using only the pulses of PD measured with the HFCT sensor corresponding to a train of reference PD pulses after removing electrical noise it is possible to obtain the Scale factor, k_q, (pC/mV) or its inverse parameter $1/k_q$ (mV/pC), as it is preferred.

Table 2 shows the results obtained for different types of discharges using the same PD instrument, which oscillate between 5.6 and 6.6 pC/mV. This means that electrical noises of a few tens of mV (e.g. 40 mV) could endanger the sensitivity of the measuring equipment above 200 pC. On certain occasions the electrical noise can reach signals much higher, which would make it impossible to measure PD except powerful filtering tools are used [6].

Table 2: Scale factors pC/mV depending on pulse waveforms.

Discharge	Upeak (mV) v.s. q (pC)	pC/mV	Waveform
Floating electrode		6,7	
Surface		5,6	
Cavity		6,7	

If a standard PD current pulse were accepted a standard scale factor could be defined.

<u>**Noise rejection performance of a PD analyser**</u>

It is the capability to reject superimposed noise on known PD pulses. It can be defined by the threshold curve of 50% error due to noise influence. This curve is determined for every charge level of a standard PD pulse by the noise magnitude for which the error of the measured PD magnitude is bigger than 50% (6 dB when it is expressed in dB) of the actual injected. The PD magnitude chosen is the PD amplitude or the pulse repetition rate. Noise magnitude should be expressed by ratio between noise amplitude and PD pulse amplitude, both measured by an oscilloscope.

The noise rejection tool can be determined by injecting standard PD current pulses (T1/T2) with a PD repetition rate of 100 pulses/s (1 pulse/10 ms) at five peak values, values uniformly distributed between minimum and maximum charge range. Simultaneously, a noise signal should be injected to the HFCT sensor by means of an isolated circuit. A digital oscilloscope with a 1GHz bandwidth and a sampling rate of 10 GS/s is used as reference measuring system for both signals the injected PD pulse and the noise signal. For every peak value of a standard current pulse, the noise amplitude is then increased from zero to the threshold level that causes the 50% error. This noise severity is measured and expressed by a per unit ratio (quotient between noise and PD pulse amplitudes measured by the reference measuring system).

This test should be repeated for different types on noises: Sinusoidal noise, white noise and power electronic noises. These last ones are included to simulate power electronic noises: subtype-1: wind plants, subtype-2: PLC in MV grids and subtype-3 HVDC converter stations.

CONCLUSIONS

A testing setup has been presented that allows the characterization of the HFCT type sensors, as well as the PD measuring instruments that operate in the high frequency range (<30 MHz) used PD monitoring of high voltage grids and the equipment installed (AC and DC). With this method is possible to compare the effectiveness of different commercial and technical approaches and know their effective capabilities against the discrimination of different sources of PD and against rejection of electrical noise to make effective diagnoses.

ACKNOWLEDGMENTS

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