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Metrology for Future Energy Transmission

FUNDACIÓN PARA EL FOMENTO DE LA INNOVACIÓN INDUSTRIAL

LCOE LABORATORIO CENTRAL OFICIAL DE ELECTROTECNIA

New Synthetic PD Calibrator to qualify PD analysers used for insulation diagnosis of HVDC and HVAC cable systems

A. Khamlichi, F. Garnacho, P. Simón, J. Rovira,

ak@ffii.es

FFII-LCOE, High Voltage Technological Center, Madrid, Spain

1. INTRODUCTION

PD monitoring using HFCT sensors has proven to be efficient to prevent insulation defects in HVAC cable systems [1] and [2]. For insulated transmission cables with lengths of hundreds of km, only HVDC cable systems can be used [3] and [4]. One disadvantage of these cable systems, unlike HVAC cables, is that they do not have link boxes to place HFCT-type sensors every 500 m or 700 m, while in HVDC cables a longer distance of around 10km is required. Consequently, the sensitivity of HFCT sensors used for HVDC must be higher than that required for HVAC cable systems. In both cases HVAC and HVDC transmission cable systems, the actual PD charge measurement along a cable is very important parameter because ***traveling charge of a PD pulse*** through the cable sheath of a transmission HV cable system ***remains almost constant along the cable length***

$$I_x(\omega) = I_o(\omega) \cdot e^{-\gamma\ (\omega)\cdot x} \qquad (1)$$

$$\text{where: } \gamma(\omega) = \sqrt{(r + j \cdot \omega \cdot l} \cdot \sqrt{(g + j \cdot \omega \cdot c} \qquad (2)$$

$$q_x = I_x(0) = I_o(0) \cdot e^{-\gamma\ (0)\cdot x}(3) \rightarrow \quad q_x = q_o \cdot e^{-\sqrt{r \cdot g}\cdot x} \quad (4)$$

For example, for a transmission HVDC 320 kV cable system of 2,500 mm^2 Cu with r=150 mΩ/km and g=10^{-6} S/km the traveling charge at 10 km will be:

$$\boldsymbol{q_{10km} = q_o \cdot e^{-0,0039} = 0,996 \cdot q_o} \qquad (5)$$

The PD pulse amplitude attenuates as the pulse travels along the cable system, but its width increases almost in the same proportion to keep constant the traveling charge along the cable system (Fig. 1).

$$q = \int_0^{\infty} i\,(t) \cdot dt = i_{peak} \cdot \int_0^{\infty} i_{pu}\,(t) \cdot dt = i_{peak} \cdot T_{PD} \quad (6)$$

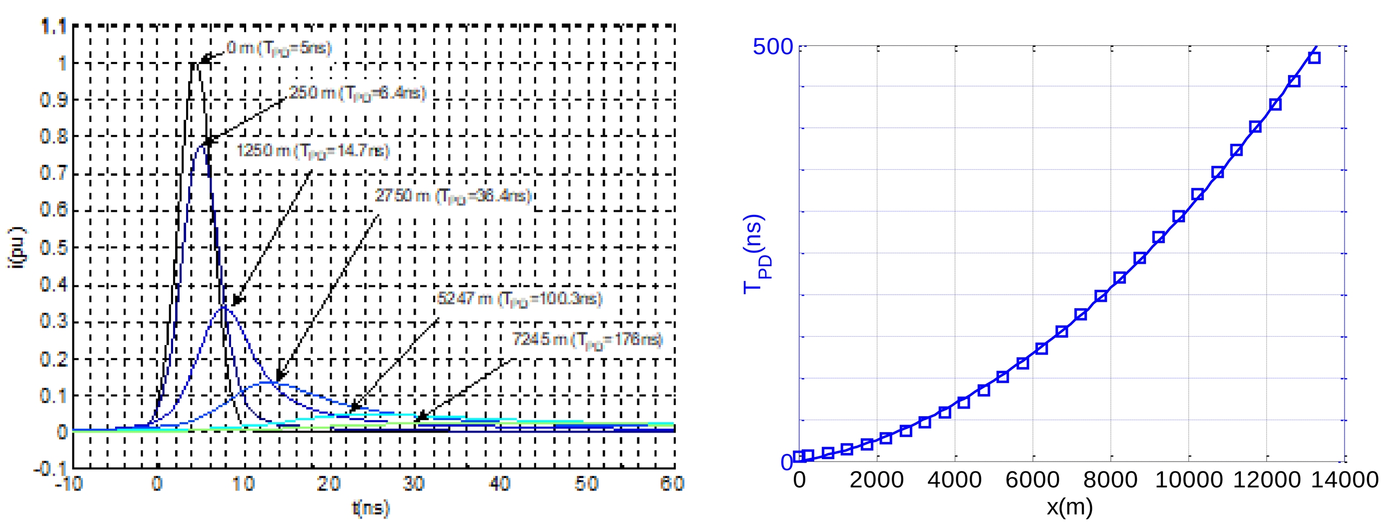

Fig.1 PD pulse distortion traveling along a HVDC cable system, b) Growing of the PD time, TPD, traveling along a HVDC cable system with an initial T_{PD} =5 ns.

2. REFERENCE MEASURING SENSOR FOR PD MEASUREMENTS

A measuring system using HFCT acquires the most part of pulse frequency content of the PD pulse (Fig. 2), in such a way that the original pulse can be reconstructed. For this reason, unlike an IEC 60270 measuring system, the upper cut-off frequency f_2 of the HFCT transfer impedance, Z_s, must be higher than the upper frequency limit f_c of the pulse spectrum. The PD sensitivity of an HFCT sensor is related to its transfer impedance value, Z_s. The higher the value of the transfer impedance, the higher the sensor sensitivity.

$$k\left(\frac{pC}{mV}\right) = \frac{q}{u_{peak}} \approx \frac{i_{peak} \cdot T_{PD}}{Z_s \cdot i_{peak}} = \frac{T_{PD}(ns)}{Z_s\left(\frac{mV}{mA}\right)} = \frac{1}{s} \qquad (7)$$

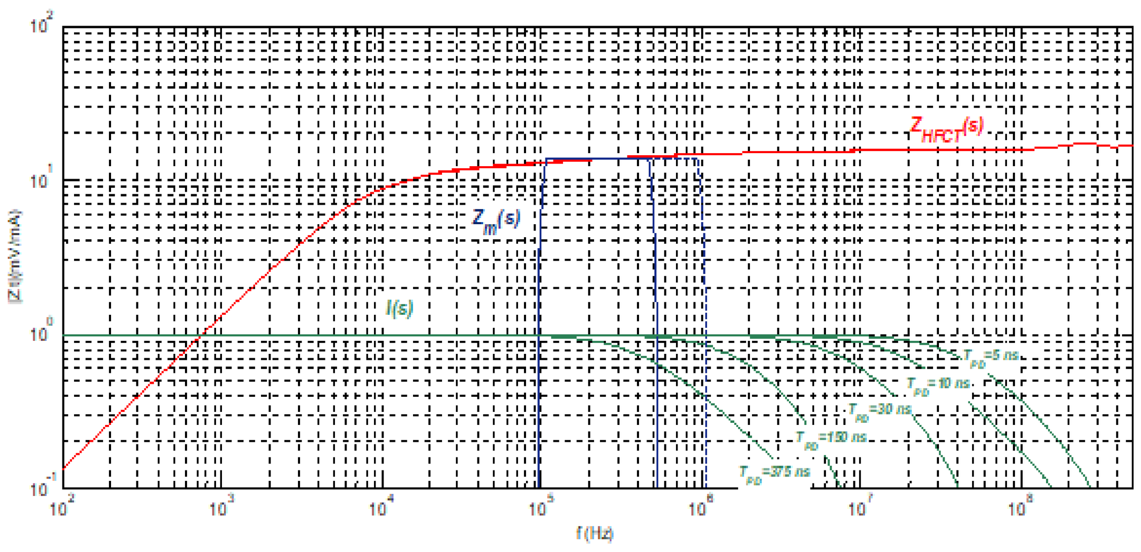

Fig.2 *I(f)*= Normalized spectrum of different PD pulses: T_{PD}=30 ns, 150 ns and 375 ns; b) Z_m(f): Measuring system according to IEC 60270 c) Measuring system using HFCT sensor whit a flat response from 100 kHz up to 500 MHz.

3. SYNTHETIC PD CALIBRATOR

The developed synthetic PD calibrator follows the electrical circuit of Fig. 3. It consists of an arbitrary waveform generator, AWG, (1), of 400 MHz bandwidth, 1.25 Giga-Samples/s and 50 Ω of internal resistance (2), that reproduces PD pulses in a pre-defined sequence according to a PD event train chosen from a reference data base (3) to generate a calibration PD pulse train or to emulate a real PD pulse train representative of an insulation defect (e.g a cavity, corona, surface or floating). Each PD event train that lasts several seconds up to several minutes is an array of charge values together with their starting times (q_i, t_i). A pulse train is generated using the chosen PD event train, giving the same waveform to each charge event, (q_i, t_i), by means of the analytical functions described in section 3.4 and saved in the reference pulse waveform database (4). The generated PD pulses are injected in a current loop matched at 50 Ohm with a terminal load resistance of 50 Ohm, R_{load}, (5).

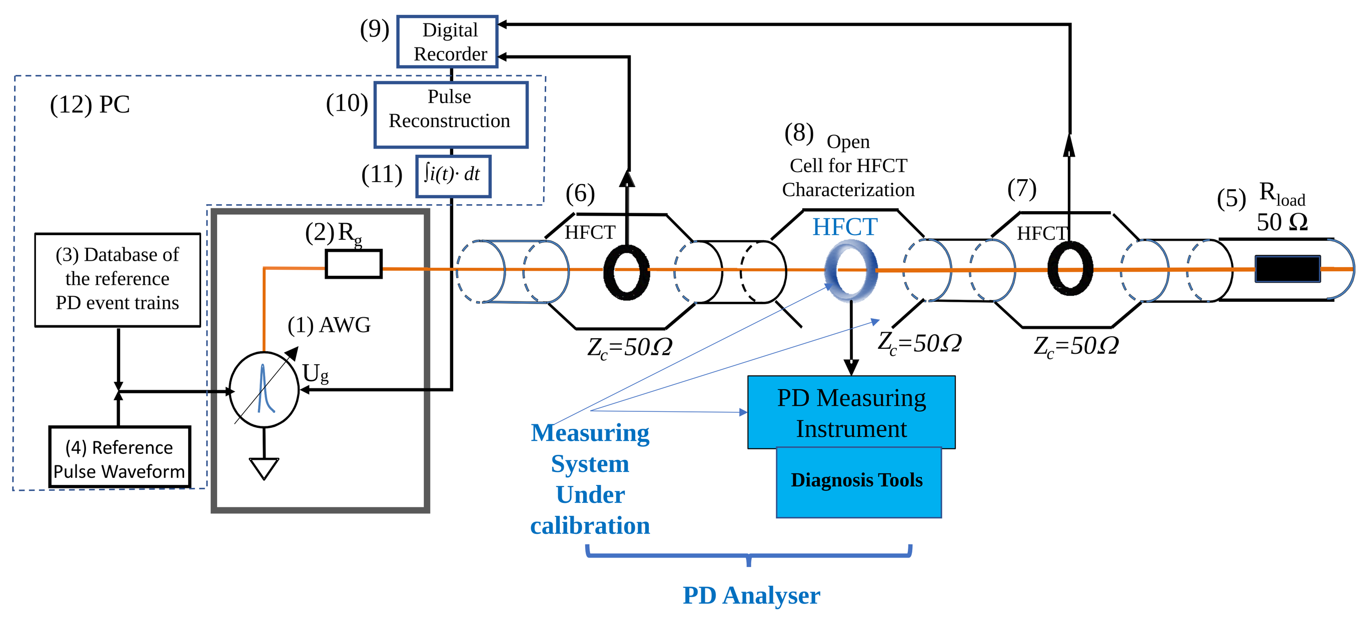

Fig.3 Components of the reference synthetic calibrator

Each generated PD current pulse is acquired through two improved HFCT sensors (6) and (7), with a high transfer impedance value of 15 mV/mA each, placed before and after the opened testing cell (8) where the HFCT sensor of the PD analyzer under characterization must be located. The two sensors are used in order to reduce uncertainty and as a mean of assuring that the HFCT under test is properly matched preventing signal reflections. The output signals of HFCT sensors (6) and (7) are measured by a digital recorder of 200MHz bandwidth (1 Giga-Sample/s with 8 bits resolution or 0,5 GSamples/s with 12 bits resolution) (9). A PC (12) is used to upload the reference PD event trains (3) and the reference PD pulses (4). The PC is also used for pulse reconstruction (10) and for pulse integration (11) by means of a signal processing software described in 5.4. The resulting charge (11) is used as feedback to regulate the voltage amplitude of the AWG to achieve the PD pulse charge previously set. A general overview of the developed synthetic calibrator is shown in Fig. 4.

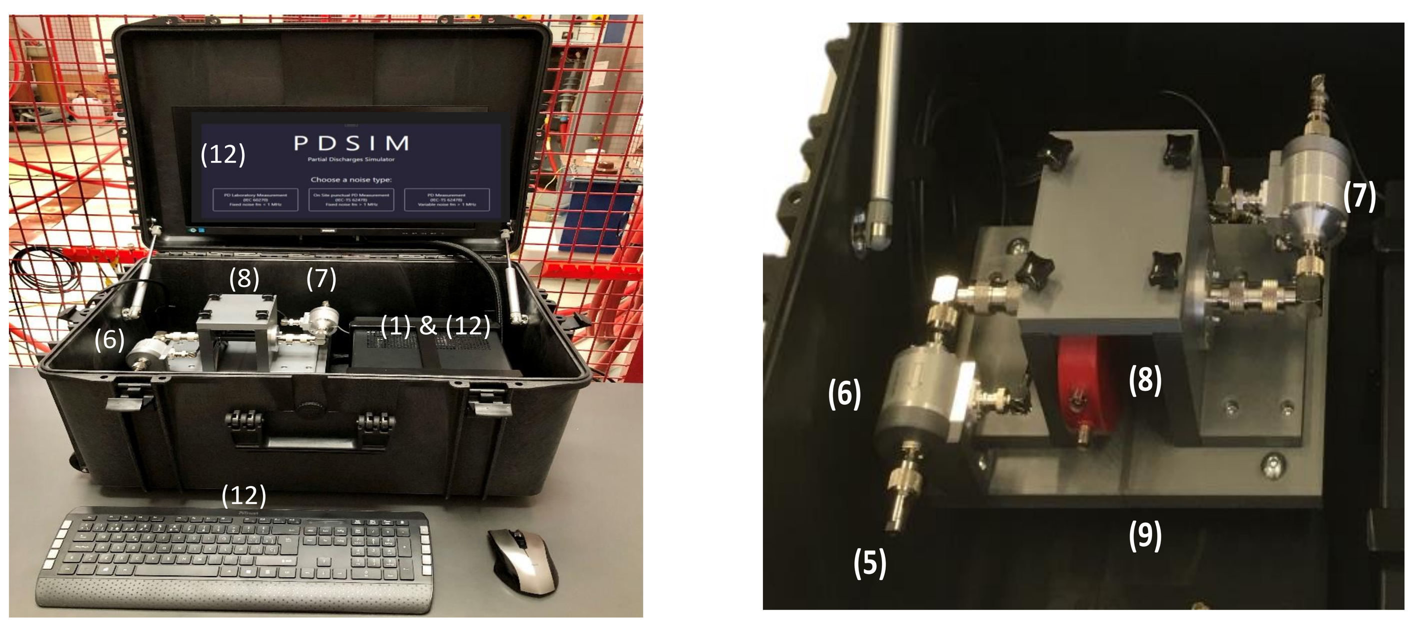

Fig. 4. Practical implementation of the calibration setup for qualification of PD analysers

The AWG generator can use an internal memory of 4 GB or an external memory of 240 GB. When the external memory is used the PD pulse generation is carried out in streaming mode with a maximum transferring speed of 100 MS/s. Up to 20 minutes of PD pulse generation can be played with A sampling interval of 10 ns. However, for some metrological tests the maximum data transfer capacity up to 1.2 GS/s) is needed, using its internal memory of 4 GB. For example, to generate PD pulses with a very short T_{PD} of 8ns, about 30 samples spaced 0.8 ns are used. At maximum data transfer capacity speed, a length record of 1.6 s can be played. For other metrological tests a transfer rate of 1 GS/s is used, to generate PD pulse trains of 2 s length.

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4. SIGNAL RECONSTRUCTION

The reconstruction of the original PD pulse measured by the reference HFCT sensors is required to determine the electrical charge of the original PD current pulse. The transfer function in the frequency domain of the HFCT sensor was previously determined by a characterization test (Fig. 2). The HFCT transfer function can be fitted by expression (7) as products of quotients of poles and zeros or by expression (8) as sum of poles with their residuals..

$$\boldsymbol{Z_t(s)} = \prod_{i=1}^{n} \frac{s-z_i}{s-p_i} \qquad (8)$$

$$Z_t(s) = \sum_{i=1}^{n} \frac{r_i}{s-p_i} + r_0 \qquad (9)$$

The transfer function of the reference HFCT sensors was fitted by formula (8) with eight poles and nine residues (Fig. 5). It can be observed that the fitted curves are overlapped to the measured ones

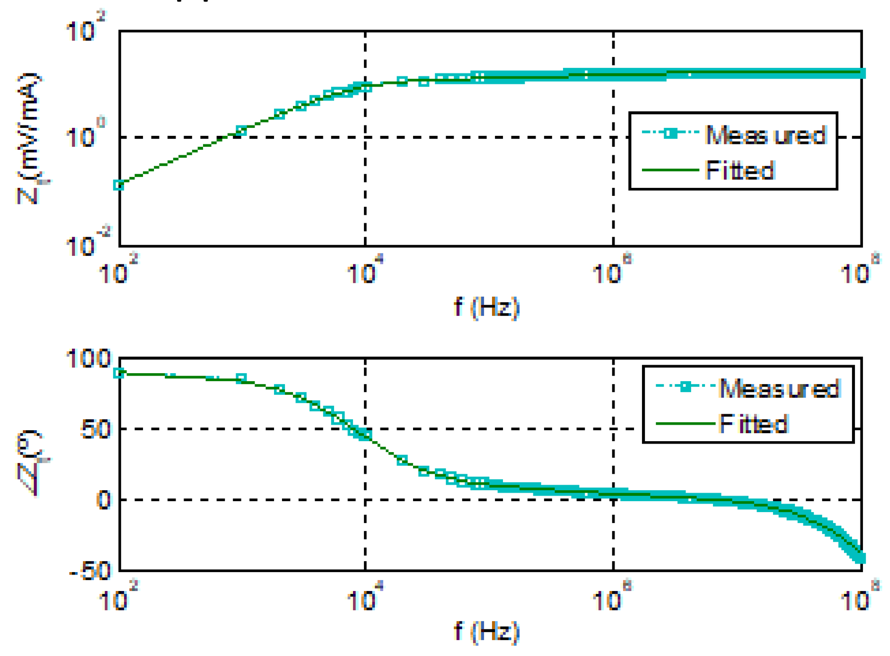

Fig.5, Fitting of the transfer impedance using the mathematical expression (8).

According to state theory applied to continuous-time systems [5], [6] the current PD pulse at the output of the sensor terminals, u(t) can be determined in the time domain by means of state variable x(t).

$$\begin{aligned} \dot{x}(t) &= A \cdot x(t) + B \cdot i(t) \\ u(t) &= C \cdot x(t) + D \cdot i(t) \end{aligned} \qquad (10)$$

Where:

$$A = \begin{bmatrix} p_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & p_n \end{bmatrix} \quad (11), \qquad B = \begin{bmatrix} 1 \\ \dots \\ 1 \end{bmatrix} \quad (12)$$

$$C = [r_1 \quad \cdots \quad r_n] \quad (13), \qquad D = r_0 \quad (14)$$

This continuous-time equation system represented by equation system (10) can be transformed to its equivalent discrete system by the integral approximation method, considering a constant interval sampling h_s.

Three different PD pulse signals measured by means of the reference HFCT sensor, with different T_{PD} each one (7 ns, 37 ns and 300 ns) have been reconstructed applying this approach. The original signal generated, the signal at the output of the reference HFCT sensors and the reconstructed signal are shown in Fig. 6. It can be observed that the HFCT does not drastically change the original signal due to its good characteristics. It is also observed that reconstruction is very good because the reconstructed signal is overlapped to the original one.

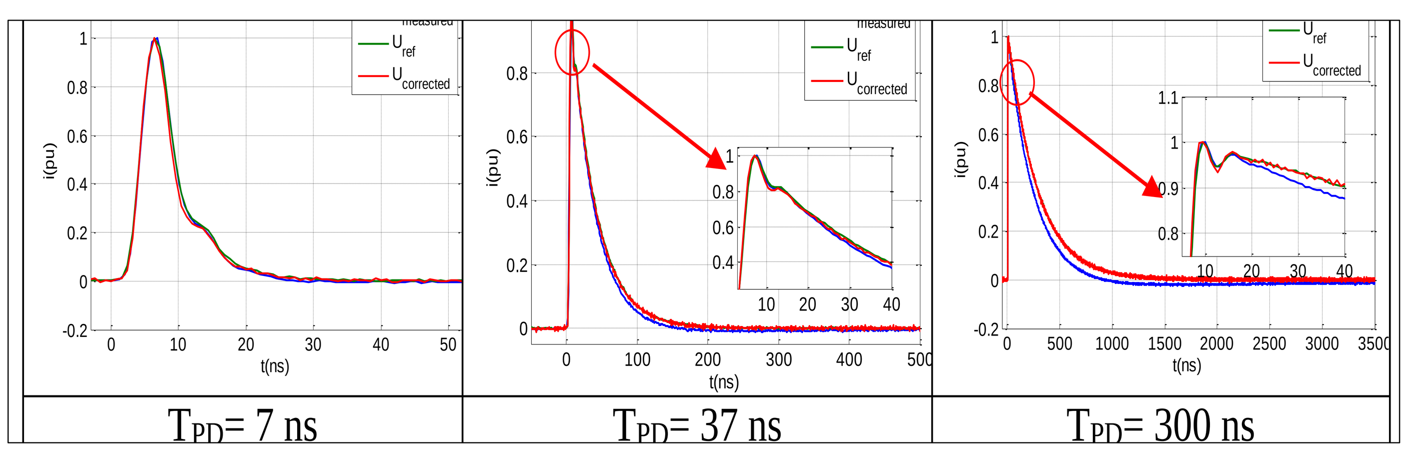

Fig. 6. Reconstruction of PD pulses. Measured signal (blue curve). Original signal (green curve). Reconstructed signal (Red curve)

The maximum and minimum charge values with their uncertainties of the developed synthetic PD calibrator are shown in Table 1. They change depending on the PD pulse width.

Table 1
Maximum and minimun charge values

T_{PD} (ns)	$q_{max} \pm U$ (pC)	$q_{min} \pm U$ (pC)
8.0	320 ± 2%	2.0 ± 1.0 pC
16.0	640 ± 2%	2.0 ± 1.0 pC
37.5	1500 ± 2%	2.0 ± 0.5 pC
75.0	3000 ± 2%	2.0 ± 0.5 pC
150	6000 ± 2%	4.0 ± 2.0 pC
375	15000 ± 2%	10.0 ± 5.0 pC

Linearity characterization of the Synthetic PD calibrator has been anayzed generating PD pulse trains with the same PD pulse waveform (T_{PD}=75 ns) but different PD pulse peak value. Each pulse train is made up of consecutive bursts of 4 pulses every 10 ms (n=400 pulse/s) separated by 1 ms between them. The linearity is better than ±0,8% or ±0,3 pC, whichever is greater. (Table 2).

Table 2
Linearity test for PD pulses with TPD=75 ns

Charge from 2 pC to 3 nC (T_{PD}=75 ns)	Error (%)	Error (pC)
500 – 3,000	**±0.8%**	-
50 - 200	**±0,4%**	-
2 – 50	**-**	**±0.3 pC**

5. CONCLUSIONS

The developed Synthetic PD Generator can generate PD pulse trains of stable charge values from 2 pC to 15 nC with an uncertainty of less than ±2% or ± 1 pC, whichever is greater, except for T_{PD}=150 and 375 ns (see Table 1). It can also reproduce PD pulse trains of the same sequence as actual representative defects (cavity, surface, floating potential, corona, SF6 protrusion, SF6 mobile particles, etc.) from an insulation defect database, which was previously generated to perform Diagnostic Tests.

A state variable model have been developed and implemented for the reconstruction of the pulse signals, i(t), using the transfer function of the developed reference HFCT sensor, and the voltage signal at the output of the HFCT sensor, u(t). The charge of each PD pulse, q, is determined by applying the final value property of the Laplace transform to the function, q=I(s=0), of the reconstructed current signal i(t).

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