

Error in the measurement of partial discharge pulses according to the frequency response of HFCT sensors

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Abstract— The measurement of partial discharges (PD) in HV installations by means of high-frequency current transformers (HFCT) is being extended progressively in recent years, as they are affordable non-invasive sensors that can be easily installed. Several manufacturers provide in their data sheets the technical characteristics considered most relevant. However, there is no formal definition of these characteristics and/or minimum requirements to be met for such type of sensors, nor objective procedures to measure and quantify them. A new European EMPIR Project [1] aims to develop a characterization procedure for PD measuring systems. The main objective of this article is to analyze some of the most relevant characteristics of an HFCT sensor and to present test-sets to be used for obtaining them, especially its frequency response, as well as its EMC immunity, and their impact on the measured PD signals.

Keywords— *sensor phenomena and characterization, performance evaluation, partial discharges, insulation testing, condition monitoring*

I. INTRODUCTION

Partial Discharge measurement is one of the most important diagnosis methods [2] and [3] for predictive maintenance of the high voltage cable systems.

Different non-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 [4]. High Frequency Current Transformers (HFCT) are commonly used as sensors for the PD measurements in high voltage grids. Several manufacturers provide in their data sheets the technical characteristics considered most relevant, such as the transfer impedance expressed in mV/mA, the conversion rates for millivolt values measured at equivalent pico-coulombs (mV/pC), the frequency range and the saturation levels of the sensors. However, there are no objective procedures to measure and quantify these parameters, nor criteria to establish the minimum requirements to be met based on the expected pulses; the latter depending on the defects in the dielectrics present in the equipment or installation to be monitored (cable system, power transformer, GIS, rotary

machine, etc.). The characterization in the frequency domain in combination with pulse measurements representative of HV networks in the time domain, enables the correlation of the measurements made. A specific test setup that combines the standardized method according to IEC 60270 [2], with the unconventional method that uses HFCT sensors is presented. The research carried out enables the establishment of robust measurement procedures, with known uncertainties and clear requirements to be met by HFCT sensors used in HV networks.

II. RELEVANT CHARACTERISTICS OF HFCT SENSORS

A. Transfer impedance of an HFCT sensor: Sensibility

The frequency response is a widely used and recognized characteristic of any sensor and it could be considered as its fingerprint. For a HFCT sensor, the frequency response relates the output of the sensor (voltage signal) to the input quantity to be measured (current signal). This ratio has units of impedance and it is known as the transfer impedance $Z_t(f)$, that depends on frequency value. It is calculated by the quotient of output rms voltage, V_{out} , and the input rms current, I_{in} , for sinusoidal signals of different frequency values, f .

$$Z_t(f) = V_{out}(f) / I_{in}(f) \quad (1)$$

The transfer impedance of a HFCT has a linear behavior with the frequency for frequency values lower than a f_1 level, working as inductance, which L value is given by:

$$L = \frac{V_{out}(f) / I_{in}(f)}{2\pi \cdot f} = Cte \quad \text{for } f < f_1 \quad (2)$$

However, HFCT sensor works as a current transformer from f_1 to f_2 , with a transfer ratio $r(f)$. This ratio is used to estimate the transfer impedance assuming as a load impedance the input impedance of the measuring instrument (50Ω):

$$Z_t(f) = I_{out}(f) \cdot Z_{load} / I_{in}(f) = 50 / r(f) \quad (3)$$

Where $r(f)$ is the current transfer ratio that depends on the frequency value and consequently it affects to the transfer impedance. It is desirable that the transfer impedance be as flat as possible within the operating frequency range (f_1 - f_2) of the HFCT sensor, considering f_1 and f_2 the minimum and the

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maximum frequency measuring limits, respectively. A rated gain Z_s of the transfer impedance should be defined by the manufacturer for the operating frequency range f_1 - f_2 . HFCT sensors are very useful for partial discharge current if their transfer impedances $Z_t(f)$ remain close to Z_s and the phase angle is also close to zero, because the PD signal will be transmitted by the HFCT sensor without a significative signal distortion. A maximum deviation value between the transfer impedance $Z_t(f)$ and Z_s in the frequency range f_1 - f_2 , around 5% is a reasonable limit for PD measurements. The HFCT sensor bandwidth, Δf , is also defined by a lower and an upper frequency limits, f_A and f_B of $Z_t(f)$, for which the gain does not differ more than ± 3 dB of Z_s , but the frequency operating range (f_1 - f_2) is a functional data much more useful for measurement purposes than the sensor bandwidth Δf . The recommended units for expressing the gain frequency characteristic are mV/mA, avoiding transforming this gain to decibels.

B. Time domain response of HFCT sensors for different pulse waveshapes

This test is intended for obtaining the time response of a HFCT sensor when a considered PD current pulse is measured by it. The waveshape of the input PD current pulse will be defined by three virtual parameters (see Fig. 1): a) The front time, T_1 , defined as 1/0.8 times the interval T between the instants when the pulse is 10 % and 90 % of their peak value. b) Time to half value, T_2 , defined as the time interval between the virtual origin, O_1 , and the instant when the PD pulse has decreased to half their peak value, being O_1 the instant preceding that corresponding to 10 % of the peak value by a time $0.1 T_1$. c) PD time of a PD pulse, T_{PD} , corresponding to the area of a PD current pulse calculated in per unit of its maximum amplitude expressed in ns or (pC/mA). It represents how many charge (pC) is inside the pulse waveshape T_1/T_2 for 1 mA peak value.

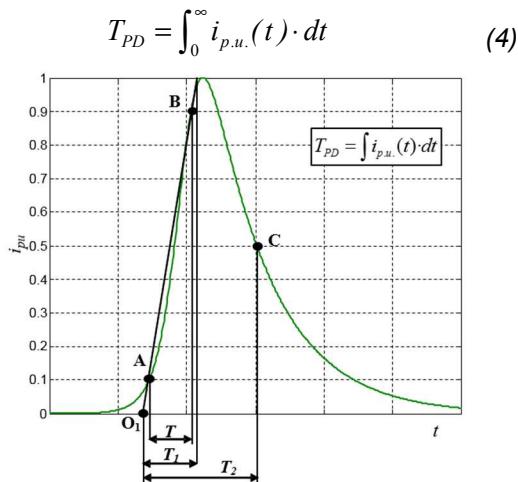


Fig. 1. PD current pulse parameters T_1 , T_2 and T_{PD} .

The charge to be measured by a measuring instrument when a generic current impulse $i_{in}(t)$ is injected through the HFCT can be expressed by means of the current pulse in per unit multiplied by its peak value I_p :

$$Q = \int_0^{\infty} i_{in}(t) \cdot dt = I_p \cdot \int_0^{\infty} i_{p.u.}(t) \cdot dt = I_p \cdot T_{PD} \quad (5)$$

HFCT sensors are commonly installed and used in locations where considerable electromagnetic interferences could be present, as power high voltage substations. Depending on the constructive design of the HFCT and materials used for its electromagnetic shielding (if considered), electromagnetic interferences falling out within the operating frequency range will induce at the output of the HFCT sensor additional signals that will distort the output signal. For this reason, it becomes necessary to evaluate the immunity of the HFCT sensor against electromagnetic interferences in the frequency operating range by an appropriate test.

III. TEST-SETUP FOR HFCT SENSOR CHARACTERIZATION

Two main test-setups were considered for characterizing a HFCT sensor. The first test-setup is used for measuring the transfer impedance and for the time domain response. The second test-setup was employed for the electromagnetic interference immunity.

A. Test-setup for obtaining the transfer impedance of a HFCT sensor and its time domain response for pulse waveshapes

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 (see Fig. 2). The measurement of the injected current sinusoidal signal, I_{in} , is transformed into a voltage signal, V_{in} , by circulating the current through the wideband impedance (Z_{load}) of 50 Ω arranged on the oscilloscope terminals (Channel 1). The oscilloscope is used in high input impedance mode, 1 M Ω , 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. Careful must be taken for the connections to the Channel 1 of the oscilloscope (it must be a direct connection), given that using a measuring cable for this connection can lead in measuring errors for the obtained phase angle, for frequencies above 10 MHz.

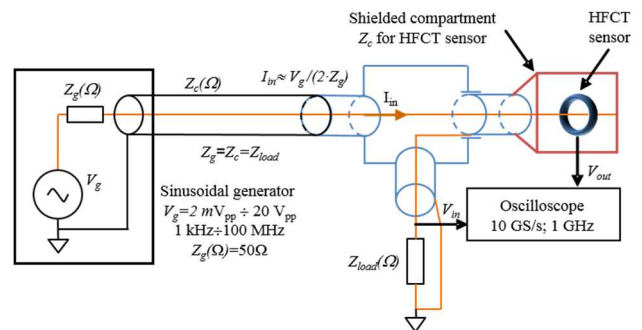


Fig. 2. Test-setup for obtaining the transfer impedance of a HFCT sensor.

The frequency generator generates sinusoidal waves of frequencies ranging from 1 kHz to 100 MHz and the oscilloscope with a bandwidth of 1 GHz, and a sampling rate

up to 10 GS/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.

The same testing setup of Fig. 2 is used to analyze the HFCT time domain response of a sensor for pulse waveshapes as the one shown in Fig. 1. It is carried out by means of an arbitrary function D/A generator of 50 MHz (100 MS/s) that generates pulse waveshapes as the one shown in Fig. 1 instead of the sinusoidal signals generated by the arbitrary generator of the test setup shown in Fig. 2.

B. Test-setup for obtaining the electromagnetic interferences immunity response of a HFCT sensor

The electromagnetic interferences immunity of a HFCT sensor is analyzed by an EMC immunity test. For this purpose, a GTEM cell is used (see Fig. 3). A test field strength of 30 V/m, corresponding to level 4 as IEC 61000-4-3 Standard [5], is applied at the testing position of the GTEM cell, for a frequency range between 100 kHz and 250 MHz. The sensor under characterization is located at that testing position, and their output is measured by means of the same oscilloscope used for the transfer impedance characterization. The signal induced at the HFCT sensor output is then represented as a function of the frequency.

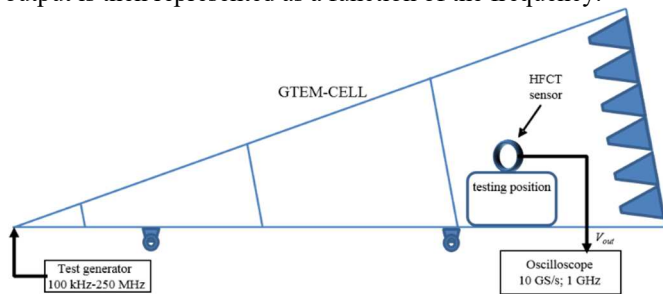


Fig. 3. Test-setup for obtaining the electromagnetic interferences immunity response of a HFCT sensor.

IV. MEASUREMENT RESULTS FROM HFCT SENSOR CHARACTERIZATION

Three commercial HFCT sensors from different manufacturers were tested. Table I summarizes their main constructive data.

TABLE I. MAIN CONSTRUCTIVE DATA FOR THE THREE TESTED COMERCIAL HFCT SENSORS

Sensor Name	Shielded	Constructive data		
		Inner diameter (mm)	Outer diameter (mm)	Width (mm)
Sensor 1	YES	50	113	25
Sensor 2	NON	50	113	25
Sensor 3	YES	50	100	34

A. Measurement results for the transfer impedance of HFCT sensors

Fig. 4 shows the measured transfer impedances for the three tested HFCT sensors. Both gain and phase angle are represented as a function of the frequency.

Table II summarizes the obtained results from the measured transfer impedances of the Fig. 4. The widest operating frequency range (f_1 - f_2) in which the transfer impedance does not change more than 5% is determined. Using this frequency interval, the rated transfer impedance Z_s was calculated.

TABLE II. MAIN OBTAINED TRANSFER IMPEDANCE CHARACTERISTICS FOR THE THREE TESTED COMERCIAL HFCT SENSORS

Sensor Name	f_1 - f_2 (MHz)	Z_s (mV/mA)
Sensor 1	0.5÷25	8.5
Sensor 2	0.3÷2.5	12.0
Sensor 3	0.3÷40	4.7

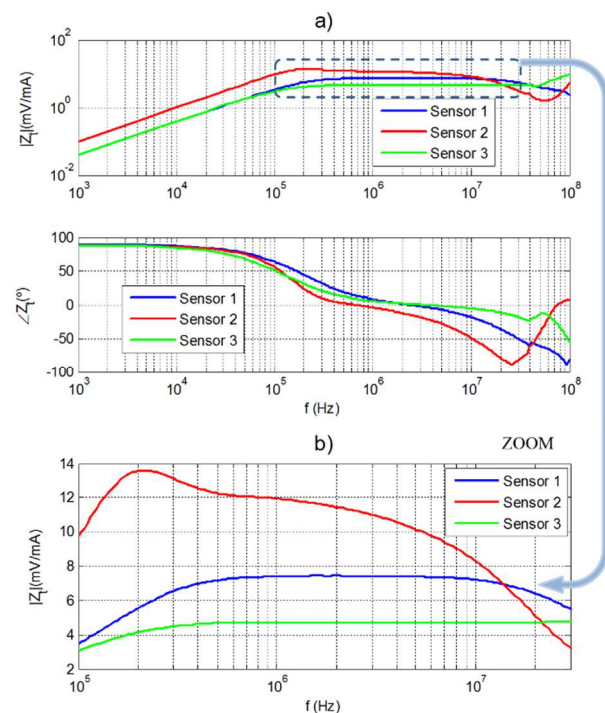


Fig. 4. Measured transfer impedances for three tested HFCT sensors. a) Gain in logarithmic scale and phase angle. b) Detail zoom of the gain in linear scale.

For low frequencies, all transfer impedances from Fig. 4 exhibit a shape like a first order high pass filter, with a cutoff frequency of about 200 kHz. For frequencies above 10 MHz the behavior of the transfer impedances is different for the three HFCT sensors.

As it is shown in Fig. 4 b) Sensor 2 presents a high gain (12 mV/mA) but its operation frequency range is too low (0,3 – 2,5 MHz) because its response frequency is not flat. Sensor 3 presents a very flat frequency response in a wide frequency range from 0,3 to 40 MHz but its gain is the lowest one 4,7 mV/mA. Sensor 1 presents a flat frequency response in a reasonable operation frequency range from 0,5 MHz to 25 MHz with a good gain value (8,5 mV/mA).

B. Time domain response of HFCT sensors for different pulse waveshapes

Three different PD pulses were injected to each sensor in this test: Waveform 1, Waveform 2 and Waveform 3 are shown on the Fig. 5 with their rated parameters were defined in Section II.B.

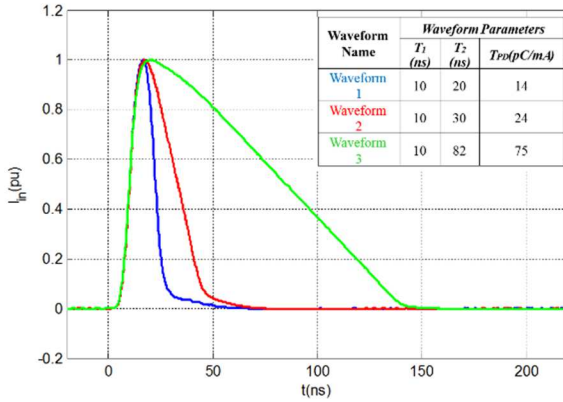


Fig. 5. Waveshapes of the three pulses applied for the time domain response of tested HFCT sensors.

Fig. 6 shows the waveforms recorded at the output of the three tested HFCT sensors for each input waveform 1, 2 and 3. All of them have a negative oscillation component due to their frequency response. The equivalent charge value Q_e , measured for each input injected waveform of T_{PD} (see formula (4)) can be estimated from the output voltage signal assuming the ratio between the output signal $v_{out}(t)$ and the input current $i_{in}(t)$ remains constant to the gain of the transfer impedance, Z_s , during the integration time limited up to the instant t_1 corresponding to the first zero crossing. This integral represents the maximum area, A_p , enclosed by the output signal.

$$T_{PD} = \int_0^{\infty} i_{p.u.}(t) \cdot dt \approx \int_0^{t_1} \frac{v_{out}(t)}{Z_s} \cdot dt = \frac{A_p}{Z_s} = Q_e \quad (7)$$

The Table III summarizes the calculated front time T_1 , time to half value T_2 and the “proportional areas” A_p , obtained for recorded waveforms at the output of the HFCT sensor. The Sensor 1 gives time parameters T_1/T_2 of the output closest to the input signals due to the flat response in the operation frequency range.

Table IV summarizes the obtained values of estimated charge Q_e to the real injected charge T_{PD} , for all sensors and

for the three waveforms. The error, $\epsilon = 100 \cdot (Q_e - T_{PD}) / T_{PD}$, between each Q_e value and the corresponding T_{PD} was also evaluated and shown in this table. Sensor 2 whose response frequency is not flat presents bigger errors, in comparison with Sensor 1 and Sensor 3, whose response frequency is very flat in a wide frequency range..

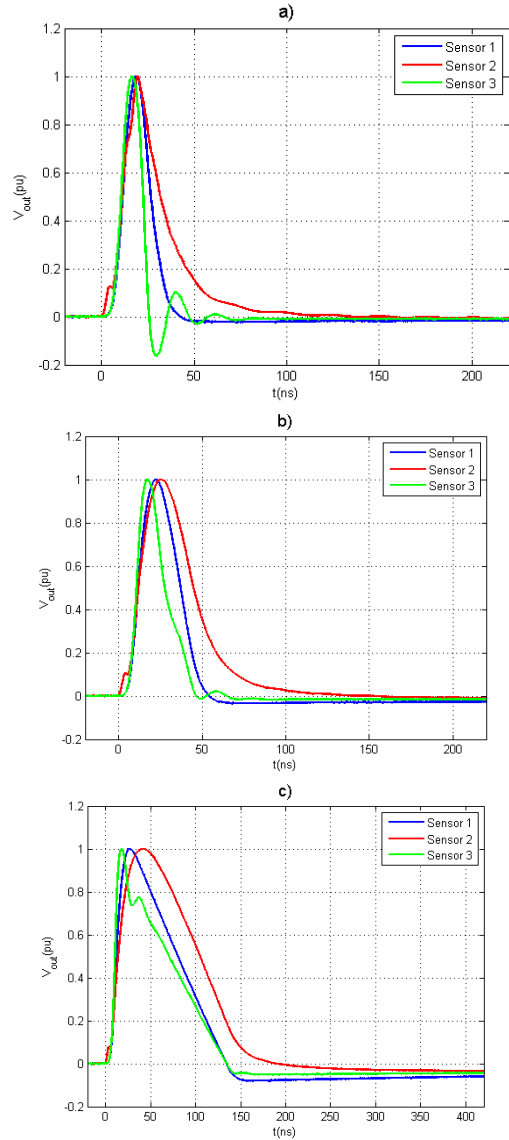


Fig. 6. Waveforms recorded at the output of the three tested HFCT sensors referred to 1 p.u.: a) For Waveform 1 as input, b) For Waveform 2, c) For Waveform 3.

TABLE III. T_1 , T_2 AND A_p CALCULATED FROM THE OUTPUT OF THE THREE TESTED HFCT SENSORS AND FOR ALL TESTING PD PULSES

Sensor Name	Waveform 1		Waveform 2		Waveform 3	
	T ₁ /T ₂ (ns)	A _p (mV·ns/mA)	T ₁ /T ₂ (ns)	A _p (mV·ns/mA)	T ₁ /T ₂ (ns)	A _p (mV·ns/mA)
Sensor 1	12.1/22.4	112	13.4/32.2	195	16.3/75.7	596
Sensor 2	10.9/27.8	143	15.4/39.8	252	25.4/101.2	818
Sensor 3	8.8/18.2	62	9.1/22.8	104	9.25/65.6	328

TABLE IV. Q_e AND ϵ CALCULATED FOR THE THREE TESTED HFCT SENSORS AND FOR ALL TESTING PD PULSES

Sensor Name	Sensor 1		Sensor 2		Sensor 3	
	Q_e (pC/mA)	ϵ (%)	Q_e (pC/mA)	ϵ (%)	Q_e (pC/mA)	ϵ (%)
Waveform 1	13.1	-4.4	12.0	-12.4	13.2	-3.6
Waveform 2	23.0	-3.4	21.0	-11.8	22.1	-7.1
Waveform3	70.1	-7.0	68.2	-9.5	69.7	-7.6
Average error	4.9%		11.2%		6.1%	

The Q_e obtained values are plotted vs the T_{PD} of each pulse waveform, as shown on Fig. 7. The linear behavior between Q_e and T_{PD} demonstrates that area enclosed by the first oscillation of the output signal Q_e is proportional to the injected charge T_{PD} (pC/mA) in the frequency range f_2-f_1 where Z_s remains constant.

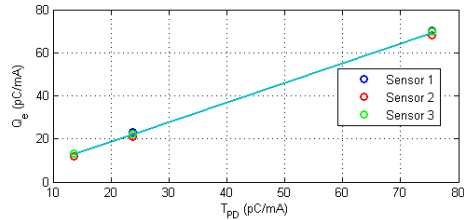


Fig. 7. Q_e parameter plotted vs the T_{PD} of the PD testing pulses, for the three tested HFCT sensors, and a linear fit of the data.

C. Measurement results for the electromagnetic interferences immunity response of HFCT sensors

Fig. 8 shows the obtained immunity responses for the three tested HFCT sensors as a function of the frequency. For frequencies up to 3 MHz, the responses are almost constant and similar in the three sensors, about 13 mV for Sensor 2, and about 7 mV and 1.3 mV for Sensor 3 and Sensor 1, respectively. For frequencies above 3 MHz, Sensor 3 exhibit a larger interference at its output, between 5 and 25 times, in comparison with Sensor 3. It is justified because sensor 3 does not have any shielding protection, while the others two sensors have a copper and aluminum shielding.

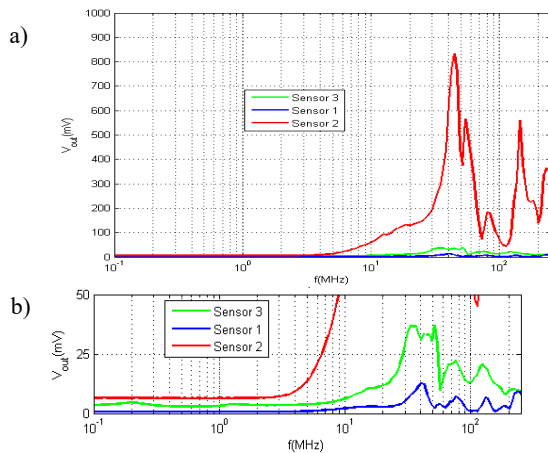


Fig. 8. a) Electromagnetic interference immunity for the three tested HFCT sensors, as a function of the frequency. b) Zoom of the same responses.

V. CONCLUSIONS

Testing setup for evaluating the main characteristics and responses for HFCT sensors has been presented. Different commercial sensors were tested and compared for PD pulses measurements. Analyses from the obtained results allow list the following statements.

1) Transfer impedances of all sensors exhibit a shape like a first order high pass filter, inductive behaviour, with a cutoff frequency of about 200 kHz.

2) HFCT sensors work as a current transformer with transfer gain Z_s , that remains constant ($\pm 5\%$) in the operation frequency range from f_1 to f_2 . This frequency operation range is much shorter than the rated bandwidth given by the manufacturer.

3) Depending on the design of HFCT sensor very different frequency operation ranges f_1-f_2 were observed.

4) It is more important to assure an operation range f_1-f_2 , from 0,5 MHz up to 20 MHz than to have a big rated gain Z_s if it works only a short operation frequency.

5) The real injected charge can be estimated by the area enclosed by the first oscillation of the output signal $v_{out}(t)$, A_p , if this area is divided by its gain Z_s ($Q_e=A_p/Z_s$). Sensor 2 gave the biggest average error (11.2%) in comparison with sensors 1 (4.9%) and 3 (6.15% respectively) because its frequency operation range is much shorter (0.3 MHz – 2.5 MHz) than sensors 1 (0.5 MHz – 25 MHz) and 3 (0.3 MHz – 40 MHz).

6) The sensor 1 gives time parameters T_1/T_2 of the output closest to the input signal due to its good flat response in the operation frequency range f_1-f_2 .

7) Unshielded HFCT sensors exhibit a large interference at its output and hence, low immunity against electromagnetic interferences, that can affect strongly the measured PD pulse.

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