Technical Document

Easy measurement of PD transfer impedance using network analyzer

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EASY MEASUREMENT OF PD TRANSFER IMPEDANCE USING NETWORK ANALYZER

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Abstract: IEC 60270 requires to measure the transfer impedance $Z_T(f)$ of the Partial Discharge (PD) measuring system for type, routine and performance tests. $Z_T(f)$ is the ratio of the output voltage and input current of the PD measuring system. In many cases this measurement is performed only at few fixed frequencies using a function generator (converted into a current source) and reading the output voltage either from an additional oscilloscope or the PD detector display. Determination of the -6dB and -20dB cut-off frequencies requested in the IEC 60270 standard may require interpolation between two frequencies. Covering all main filters and coupling impedance combinations is difficult, leading manufacturers to limit the measurement to a single setup. In this paper, a quick and easy method is presented to measure $Z_T(f)$ based on a Vector Network Analyzer (VNA). The VNA performs the frequency sweep, measures the input current and output voltage, performs the calculation and automatically determines the -6dB and -20dB cut-off frequencies. Two setups are covered where one is using the T/R gain-phase test ports and the second one is using the S-parameter test ports. The PD detector offers an analog output for direct connection to the VNA. The $Z_T(f)$ measurement relies only on one traceable measuring equipment hence avoiding complex test arrangements.

1 INTRODUCTION

Partial discharge (PD) measurement is a powerful method to detect insulation defects in high voltage equipment. Determination of the transfer impedance is part of the required PD detector tests as per [1]. The real purpose of the transfer impedance measurement is often mistaken because the procedure combines the frequency bandwidth measurement of the PD coupling impedance and the PD filters.

Manufacturers tend to choose a simple test arrangement based on measuring equipment which is readily available in the lab. For example, by using a function generator set to sine wave voltage V_{set} and converted into a current generator by a series resistor R_{set}. However, the injected current is not directly measured but assumed to be V_{set}/R_{set} and the output voltage is derived from the PD reading in pC.

Such test arrangements are unable to accurately detect ripple or slopes of the band pass filter. Filter characteristics may be much more stringent than required by [1]. For example, [2] specifies a 100 kHz to 300 kHz filter for transformer testing with limits of -60dB @ 15 kHz and 1 MHz, -40dB @ 25 kHz and -20dB @ 500 kHz.

Basically, it is easier to use a Vector Network Analyzer (VNA) because only one test equipment is required. The VNA allows to immediately identifying distortions originating from coupling impedance, wiring, grounding, or analog front-end filter without additional software calculations. Therefore, tracking unwanted resonances or checking performance drifts due to aging or damages after a flashover are made simple.

This paper describes the procedure and setup to measure the transfer impedance and highlights the major benefits of an analog output in a fully digital PD detector.

2 TRANSFER IMPEDANCE IN PD MEASUREMENT

The next sections intend to clarify the purpose of measuring the transfer impedance $Z_T(f)$ and how this leads to the presented measurements methods. Note that the purpose and measurement of the transfer impedance used to characterize the shielding effectiveness of cables differs from the purpose of $Z_T(f)$ measurement presented in this paper.

2.1 PD Measurement Model

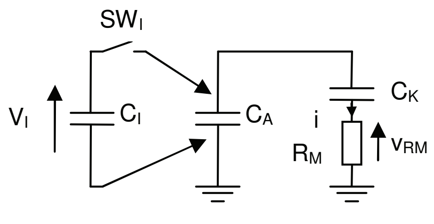

Figure 1: Basic PD measurement model

The model shown in Figure 1 recalls the basic elements of PD measurement and calibration.

C_I: PD calibrator injection capacitance

V_I: Capacitor charging or calibrator step voltage magnitude $q=C_I \cdot V_I$

SW_I: Calibrator switch

C_A: Test object capacitance in the frequency range selected for the measurement. The test object equivalent capacitance may vary with frequency.

C_K: Coupling capacitance

R_M: Measuring impedance

2.2 PD Pulse in Time and Frequency

The PD pulse voltage and the corresponding spectrum are shown in Figure 2. From [3] we obtain the time domain voltage V_{RM} across the measuring impedance assuming $C_I << C_A$

$$\mathrm{v_{RM}(t)} = \frac{q}{C_A} \cdot e^{\left(\frac{-t}{R_M \cdot C_{EQ}}\right)} \quad (1)$$

where: $q = C_I \cdot V_I$

$$C_{EQ} = \frac{C_A \cdot C_K}{C_A + C_K}$$

The magnitude of the corresponding spectrum is

$$\left|\mathrm{V_{RM}(f)}\right| = \frac{q}{C_A} \cdot \frac{1}{\sqrt{\left(\frac{1}{R_M \cdot C_{EQ}}\right)^2 + (2 \cdot \pi \cdot f)^2}} \quad (2)$$

The -6dB cut-off frequency of the spectrum defined in Equation 2 can be written as .

$$\mathrm{f_{-6dB}} = \frac{\sqrt{3}}{2 \cdot \pi \cdot R_M \cdot C_{EQ}} \quad (3)$$

Figure 2 shows the PD pulse signal and its spectrum. As described in [1] the upper cut-off frequency of the PD detector filter must be set below f_{-6dB} to ensure proper integration of the measured current into a charge.

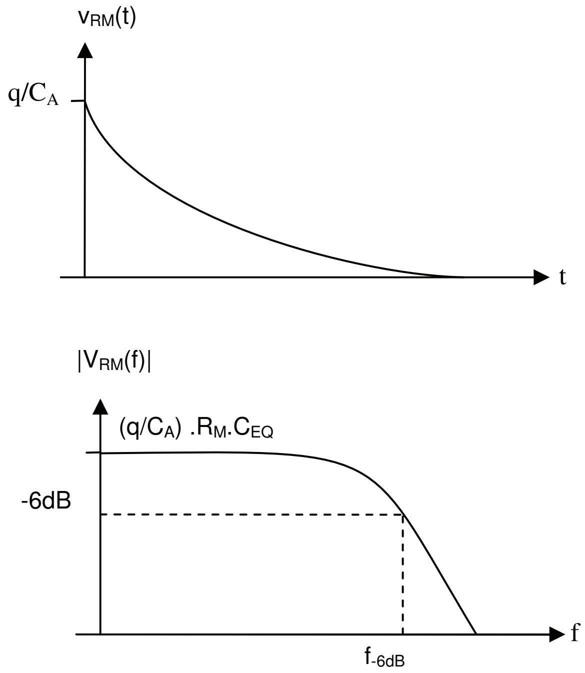

Figure 2: PD pulse in time and frequency domain

2.3 Measured Charge

In Figure 1, charge q is injected into the PD measurement setup. Based on the current i(t) flowing thru R_M we can calculate the measured charge q_m.

$$\mathrm{q_m} = \int \mathrm{i(t)} \cdot \mathrm{d}t = \int \frac{\mathrm{v_{RM}(t)}}{R_M} \cdot dt \quad (4)$$

$$\mathrm{q_m} = \frac{q}{R_M \cdot C_A} \cdot \left[-R_M \cdot C_{EQ} \cdot e^{\left(\frac{-t}{R_M \cdot C_{EQ}}\right)} \right]_0^{\infty} \quad (5)$$

$$\mathrm{q_m} = q \cdot \frac{C_K}{C_A + C_K} \quad (6)$$

The measured charge q_m is proportional to the injected charge q. The ratio $C_K/(C_A+C_K)$ is one of the major parameters defining the sensitivity of the PD measurement. It can be noticed that the ratio q_m/q is independent of R_M as long as the measuring impedance is constant, i.e. providing a flat spectrum in the measuring frequency range. This ratio will be determined at the time of PD calibration and is reflected in the PD detector calibration factor.

2.4 Transfer Impedance Z_T

The transfer impedance Z_T is defined as the ratio of the output voltage amplitude to the input current amplitude [1]:

$$Z_T = \frac{V_F}{I_{RM}} \tag{7}$$

Figure 3 depicts where current I_{RM} and voltage V_F are located in the PD test arrangement.

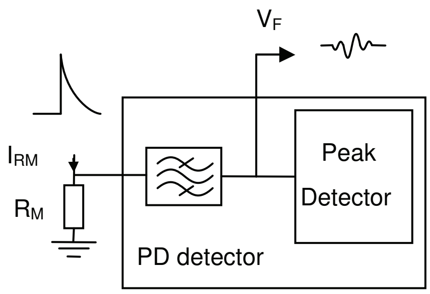

Figure 3: Input current I_{RM} and output voltage V_F for Z_T

The transfer impedance characterizes the frequency behavior of R_M including the band pass filter of the PD detector. This band pass filter serves to select a given frequency range within the PD pulse spectrum and performs a pseudo integration. The root purpose of measuring the transfer impedance is not to get a given value in ohm but to ensure that the frequency response remains constant for a defined frequency range. The absolute sensitivity value will be included in the PD detector calibration factor. The transfer impedance must be ideally flat within the -6dB limit to ensure proper integration of the PD pulse and linearity of the measurement. The measurement is assumed to be performed with a swept sine wave signal. The measuring equipment should be able to measure both a current and a voltage and calculate the ratio. This requirement perfectly fits with the definition of a VNA [4], an instrument which accurately measures s-parameters, transfer functions or impedance characteristics of linear networks across a broad range of frequencies.

2.5 The -6dB Cut-Off Frequency Limits

PD measurement is very similar to spectrum analyzer measurements in EMC testing. In that case the bandwidth (BW) is commonly defined by the -6 dB frequency limits when testing continuous wave (CW) signals. However, the response of a filter to a broadband pulse is best characterized by its impulse bandwidth (IBW). A detailed discussion of IBW goes beyond the scope of this paper. More detailed information on the definition of BW and IBW can be found in [5] and [6] which explain why not only the -6 dB limits but also the overall frequency response should be recorded. IBW is defined as an ideal rectangular filter which has the same voltage response as the considered filter under test. This is equivalent to defining a reference filter mask. The corresponding measurement methods can be found in [5,6,7]. The main difference between spectrum measurements for EMC testing and PD measurements is that PD is calibrated using a charge injection PD calibrator prior to each measurement whereas spectrum analyzers are calibrated at manufacturing time using techniques such as reference impulse generators [5].

2.6 Maintaining PD Performance in High-Voltage Environments

PD measurement systems are likely to face flashover or high-voltage impulses during operation. For such events electronic parts can be destroyed which is easily detected, but on the other hand parts can be affected such that they are no longer within their specifications: resistors with altered values, amplifiers exhibiting unexpected nonlinearities or protection diodes with increased leakage. Such effects in the measuring equipment may not be noticed until $Z_T(f)$ is verified in a performance test.

3 TRANSMISSION REFLECTION METHOD

3.1 Measurement Setup

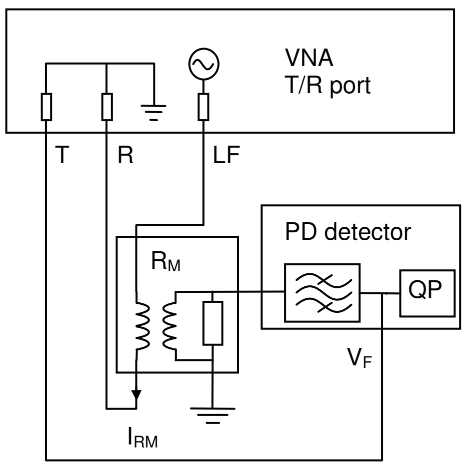

Figure 4: T/R setup for Z_T measurement

LF: Swept sine wave generator port (50 Ω).

R : Reference port (50 Ω). Voltmeter proportional to I_{RM}.

T : Transmission port (50 Ω).

In this setup, the VNA performs a direct measurement of Z_T=T/R. The VNA should be initially calibrated with LF, R and T ports connected together, e.g. using a BNC-T (THRU calibration).

3.2 Measurement Results

The band pass filter of the PD detector is set to a center frequency of 200 kHz and a bandwidth of 200 kHz. The VNA measurement is performed in the frequency range of interest with the -6dB and -20dB cut-off frequencies simultaneously displayed as shown in Figure 5.

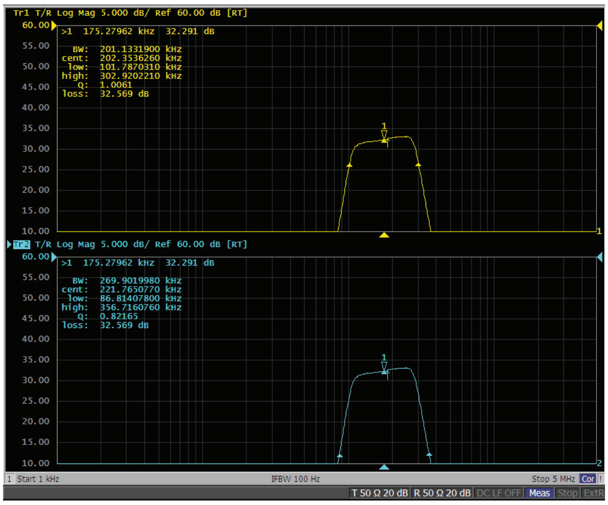

Figure 5: Z_T results using the T/R method

4 S-PARAMETER METHOD

4.1 Transfer Impedance Calculation using S-parameters

The following calculations are based on a two-port network representation of the measurement system as shown in Figure 6. All equations in this section refer to linear values of S-parameters although the VNA converts the S-parameters to a logarithmic scale in dB for display.

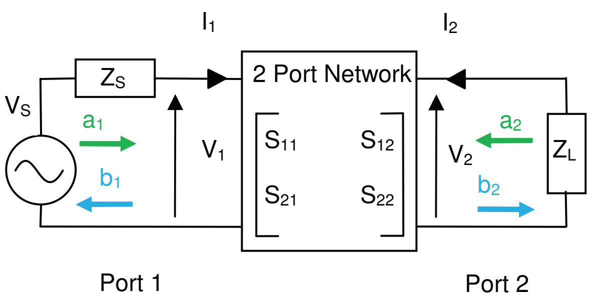

Figure 6: Equivalent two-port network representing the PD test setup

Equation 17 in [4] defines the input impedance at port 1 as a function of s_{11}:

$$Z_1 = \frac{V_1}{I_1} = Z_0 \cdot \frac{(1+s_{11})}{(1-s_{11})} \tag{8}$$

Z_0 = reference impedance (50 Ω)

The reflection coefficient at the load Z_L is defined as

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{9}$$

s'_{11} is the input reflection coefficient for arbitrary Z_L and A_v is the voltage gain for arbitrary Z_L and Z_S as defined in [4]:

$$A_v = \frac{V_2}{V_1} = \frac{s_{21} \cdot (1+\Gamma_L)}{(1 - s_{22} \cdot \Gamma_L) \cdot (1 + s'_{11})} \tag{10}$$

For $Z_L = Z_0$, i.e. $\Gamma_L = 0$ and $s'_{11} = s_{11}$ the voltage gain A_v can be written as

$$A_v = \frac{s_{21}}{(1+s_{11})} \tag{11}$$

Multiplying Equation 8 and 10 results in

$$Z_1 \cdot A_v = \frac{V_1}{I_1} \cdot \frac{V_2}{V_1} = \frac{V_2}{I_1} = Z_{TABS} \tag{12}$$

where Z_{TABS} is the transfer impedance as defined in Equation 7.

From Equations 8, 10 and 12 we get

$$Z_{TABS} = Z_0 \cdot \frac{(1+s_{11})}{(1-s_{11})} \cdot \frac{s_{21}}{(1+s_{11})} = \frac{s_{21}}{(1-s_{11})} \cdot Z_0 \tag{13}$$

And finally when removing the scaling factor Z_0

$$Z_T = \frac{s_{21}}{(1-s_{11})} \tag{14}$$

Equation 14 is coherently depending on s_{11} which can be used to calculate the input impedance and s_{21} which is the transmission factor from input to output of the two-port network. s_{12} and s_{22} do not appear in Equation 14 since we assume Z_L is equal to Z_0 and to the analog output impedance of the PD detector.

4.2 Measurement Setup

VNA port 1 should be initially calibrated using short, open and 50 Ω load standards. In addition, a port 1 and port 2 THRU calibration is required for correct s_{21} measurement.

Port 1 is then connected to the measuring impedance input and Port 2 to PD detector filter output as shown in Figure 7. Notice that the coaxial cable between the measuring impedance and the PD detector must be included in the overall Z_T measurement.

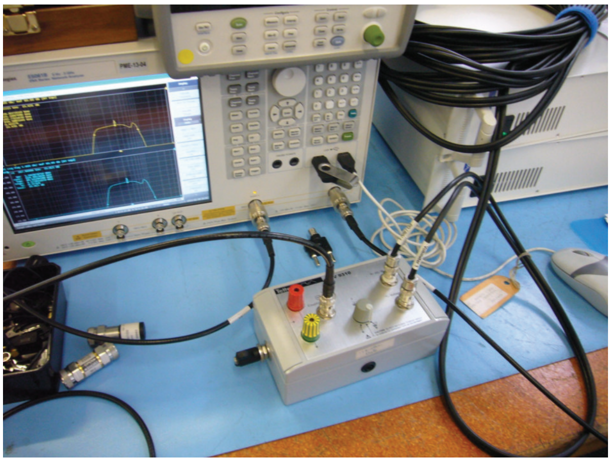

Figure 7: S-parameter setup for Z_T measurement

Finally, Equation 14 is entered in the VNA equation editor as shown in Figure 8.

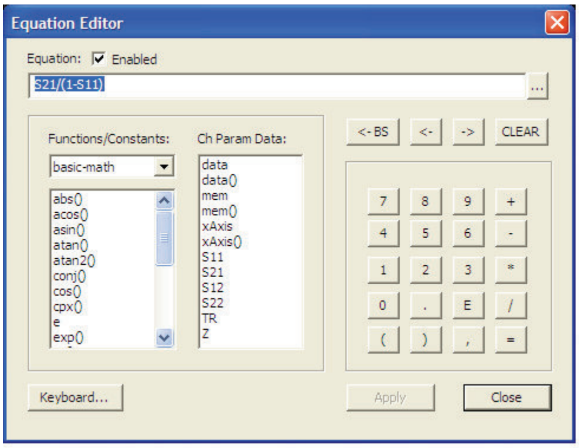

Figure 8: Entering Z_T using the VNA equation editor

4.3 Measurement Results

The results for the S-parameter method are shown in Figure 9. Upper and lower cut-off frequencies perfectly agree with the results from Figure 5 within less than 0.1 kHz.

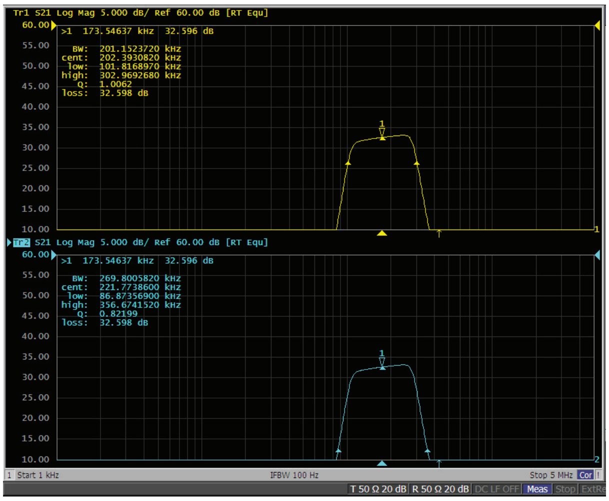

Figure 9: Z_T results using the S-parameter method

5 ANALOG FILTER OUTPUT

A short overview of analog and digital PD detectors is presented in [8]. Figure 10 is a copy of Figure 3 with added details of the filter output structure. The digital PD filter output is fed to a digital-to-analog converter (DAC), a subsequent low pass filter is used to remove spectral components of the sampling process and an additional output buffer is used for independent load drive. The filter response must be “maximally flat” to avoid any influence of the measurement results. For example, passive Butterworth LC filters as described in [9] are an adequate solution for the PD application.

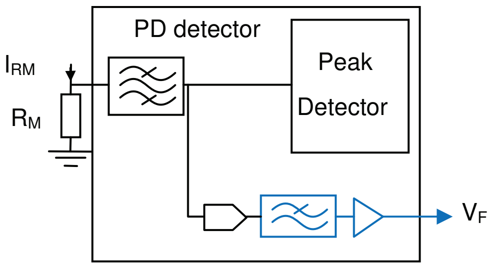

Figure 10: PD detector filter output

Additional measurements may be required to ensure flatness of the frequency response of the analog output circuit. However, any inconsistency in the DAC output signal will be clearly recognized in the overall Z_T measurement since it is very unlikely that any failure in the analog output will compensate the response of the measuring impedance and PD detector input circuits.

6 CONCLUSION

A flat response of the transfer impedance, as well as consistent -6dB cut-off frequency limits and eventually reference mask comparisons are the essential purposes of measuring Z_T. In this paper, the relation to impulse bandwidth (IBW) has been shortly discussed and two methods for the measurement of Z_T have been presented.

The T/R method requires that an insulated transformer is present in the signal path. The method best fits when testing measuring impedances included in the PD coupling capacitor. The frequency limits for valid measurements depend on the transformer primary/secondary stray capacitance. Usually this limit is in the range of several MHz.

The S-parameter method can be used up to much higher frequencies and the limitations are given by the quality of the connection, the port calibration and the availability of an analog output. No insulation is required and the measurement is performed in a setup which closely matches the final PD measurement arrangement. A simple formula relating the measured S-parameters to the Z_T function has been derived.

The major benefit of an analog output even for digital PD detectors is to facilitate the measurement of Z_T. We think this will help accredited laboratories to perform faster and easily traceable measurements.

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