



Technical Document

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capacitor resonance frequency with
help of PD pulse spectrum to check
and setup PD measurement

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BREAKING THE LIMIT OF POWER CAPACITOR RESONANCE FREQUENCY WITH HELP OF PD PULSE SPECTRUM TO CHECK AND SETUP PD MEASUREMENT

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Abstract: Partial discharge (PD) measurement is often performed without prior validation of the calibration pulse spectrum. In most cases, the correct frequency range for PD measurement is well-known but measuring the pulse spectrum is a means to verify that the PD filter limit frequencies (f_1 , f_2) fit the quasi-integration requirement according to IEC 60270. The pulse spectrum assists to detect wrong connections and defective parts as well as to verify the efficiency of HV noise suppression filters. In case of power capacitors, the resonance frequency is an essential parameter to correctly set the PD measurement frequencies in order to achieve adequate sensitivity as well as compliance with IEC 60270. This paper covers the theory and practical information required to set the correct PD frequency range with respect to the power capacitor resonance frequency. It demonstrates that PD measurement with limit frequencies set beyond the resonance frequency of the power capacitor is possible if an identical capacitor is used as the PD coupling capacitor. Sensitivity issues when using bridge connections are discussed and PD detector and coupling impedance requirements are equally covered.

1 INTRODUCTION

Partial discharge (PD) measurement requires correct setting of the PD filter limit frequencies to ensure that the quasi-integration of the PD pulses converts the measured input current into a charge in Coulombs.

The Fourier transform of the impulse response of a filter directly provides the frequency response of the filter. For proper derivation of the impulse response, the input impulse should be an ideal Dirac pulse whose magnitude is defined by the pulse area, i.e. amplitude \times pulse width. The peak magnitude of the filter output is proportional to this Dirac pulse area. However, the result is equally valid as long as the spectrum of the measured pulse slightly exceeds the filter bandwidth (BW). In that case the peak value reflects the measured pulse area, effectively “integrating” the pulse current.

Thus, it is recommended that at least the PD calibration pulse spectrum is checked to satisfy the mentioned requirement. Ideally some of the effectively occurring PD events should be checked likewise in order to ensure that the measurement is valid independent of the effective propagation path of the PD pulse in the test object.

When defining an industrial PD testing environment for a fixed product line, it is presumed that the checks described above are conducted at least once and there would be no need to regularly repeat those checks.

However, when considering power capacitors even minor changes in the test setup and improvements or modifications to the manufacturing process of

the test object can have a huge impact on the PD measurement. The root cause is linked to the resonance frequency f_R of the capacitor and to the fact that each centimeter of wiring in the measuring circuit has to be taken into account for correct measurement results. This paper covers these topics and discusses PD measurement of power capacitor at frequencies beyond the capacitor resonance.

2 SELECTING PD FILTER FREQUENCY RANGE

2.1 Impulse response and quasi-integration

IEC 60270 [1] as well as the accompanying guide ([2], Figure 18) are based on the assumption that PD measurement is valid as long as the PD pulse spectrum exceeds the upper limit frequency f_2 of the PD detector filter. However, additional characteristics like the amount of error introduced to the measurement when the PD pulse spectrum is close to f_2 as well as potential resonances within the measuring BW are needed to ensure correct measurement setup [3].

It is important to notice that the relevant PD pulse spectrum is the one of the original current pulse in the measuring impedance R_M as illustrated in Figure 1.

The measuring impedance and analog filters used to suppress power electronics switching noise are part of the PD detector filter and do not change the PD pulse BW to be considered for quasi-integration.

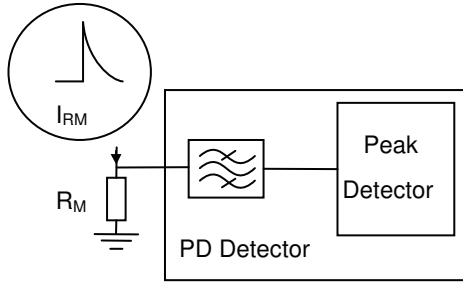


Figure 1: PD detector and measuring impedance R_M .

To explain the BW constraint for PD pulse integration we will use a first order RC filter and a rectangular pulse.

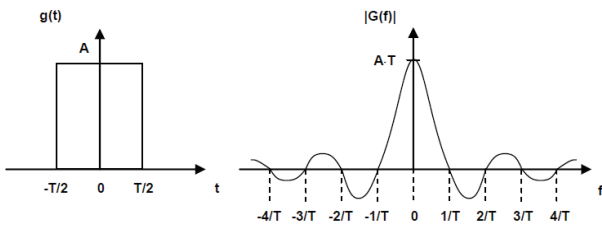


Figure 2: Rectangular pulse signal: Time domain signal $g(t)$ (left) and spectrum magnitude $|G(f)|$ (right).

The Fourier transform of a rectangular pulse of magnitude A and duration T is

$$G(f) = A \cdot T \cdot \text{sinc}(\pi \cdot T \cdot f) \quad (1)$$

From Equation 1 the -6dB bandwidth is given by

$$f_{-6\text{dB}} = \frac{0.60334}{T} \quad (2)$$

For simplicity, we use a low pass filter instead of a band pass filter (Note: band pass filter synthesis is often based on conversion techniques starting from low pass filter prototypes).

The -6dB BW of a first order RC filter is

$$f_{-6\text{dB}} = \frac{\sqrt{3}}{2 \cdot \pi \cdot \tau} \quad (3)$$

where τ is the RC time constant.

The peak magnitude of the response to a rectangular pulse according to Figure 2 is given in Equation 4.

$$V_{\text{peak}} = A \cdot \left(1 - e^{-\frac{T}{\tau}}\right) \quad (4)$$

From Equations 2–4 the normalized peak magnitude of the response to the rectangular pulse can be plotted as shown in Figure 3. For example, if the rectangular pulse BW is 10 times the filter BW, the quasi-integration of the pulse results in an

error less than 10 %. If the PD pulse BW is lower than the filter BW then the filter output equals the input pulse magnitude and hence the filter is no longer acting as an integrator.

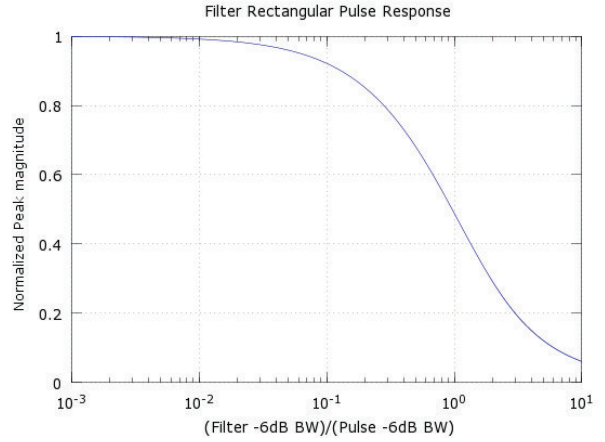


Figure 3: RC filter peak output magnitude.

With the help of the Taylor series expansion of the exponential function and neglecting higher order terms for sufficiently small values of the exponent, i.e.

$$e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \dots \xrightarrow{|x| \ll 1} = 1 + x \quad (5)$$

Equation 4 can be rewritten as indicated in Equation 6 for small values of T . This reveals that the peak magnitude of the filter output is proportional to the magnitude-time area of the pulse, i.e. proportional to the integral of the pulse waveform.

$$V_{\text{peak}} = \frac{1}{\tau} \cdot A \cdot T \quad (6)$$

Note that for $T \gg \tau$ the peak output of the filter is equal to the peak magnitude of the pulse, i.e. $V_{\text{peak}} = A$. In that case the pulse spectrum cut-off frequency is significantly smaller than the -6dB BW of the filter and hence the current pulse is no longer correctly integrated. Instead of the pulse charge the pulse current amplitude is misleadingly measured.

2.2 Practical higher order filters

The first order filter examined in the previous section is the most stringent in terms of PD pulse BW constraints. Higher order filters permit the use of lower -6dB BW ratios for the PD pulse and filter. This can be either estimated or experimentally verified with a rectangular pulse similar to the one used in Section 2.1.

2.2.1 Estimation for Butterworth filters The required BW for Butterworth filters can be estimated according to the following equation (cf. Equation 3.5.1 in [4]):

$$A_{\text{Butter}}(f) = 10 \cdot \log \left| 1 + \left(\frac{f}{f_c} \right)^{2n} \right| \quad (7)$$

where: $A_{\text{Butter}}(f)$ Attenuation at frequency f
 f_c -3dB cut-off frequency
 n Filter order

Equation 7 can be solved for the frequency ratio to obtain a desired attenuation level

$$\frac{f}{f_c} = \sqrt[2n]{10^{\frac{A_{\text{Butter}} - 3}{10}} - 1} \quad (8)$$

Note that f_c in Equation 8 denotes the -6dB cut-off frequency of the filter.

For practical measurements select a f/f_c ratio from the 20dB row in Table 1.

Table 1: f/f_c ratio for Butterworth filters.

A_{Butter} (dB)	Filter Order			
	1	2	4	6
6	1	1	1	1
20	7.0	2.6	1.6	1.4
40	70.8	8.4	2.9	2.0

2.2.2 Rectangular pulse measurement Each type of filter implementation will have a different response characteristic, hence the filters are preferably tested using a rectangular pulse. The rectangular pulse must be of constant area $A \times T$. The pulse duration T should be increased until the allowed drop in the PD reading is reached. At this point the required BW for the PD spectrum can be calculated from Equation 2.

2.3 Capacitor resonance frequency and impedance

In the present work, as opposed to the impulse analysis we have developed in [5], we will use a swept frequency analysis to focus on the PD pulse spectrum. The frequency analysis benefits from simple simulation and comparison to measurements. The top of Figure 4 is the circuit diagram for the well-known PD test setup described in IEC 60270 [1] where we have replaced the test object and coupling capacitors (C_A , C_K) by their equivalent LC model. The calibrator is modeled by an ideal swept-frequency current generator which is used to record the frequency spectrum of the current flowing in the measuring impedance R_M . The remaining circuit elements are the test object inductance L_A , the coupling capacitor inductance L_K and the wiring inductance L_W .

Based on the circuit diagram in Figure 4 and for frequencies higher than the resonance frequency f_R of the capacitor (i.e. neglecting C_A and C_K , respectively) we can calculate the ratio between

the current through R_M and the current injected by the calibrator as follows:

$$\frac{I_{R_M}}{I_{\text{PD_CAL}}} = \frac{j \cdot 2 \cdot \pi \cdot f \cdot L_A}{j \cdot 2 \cdot \pi \cdot f \cdot (L_A + L_K + L_W) + R_M} \quad (9)$$

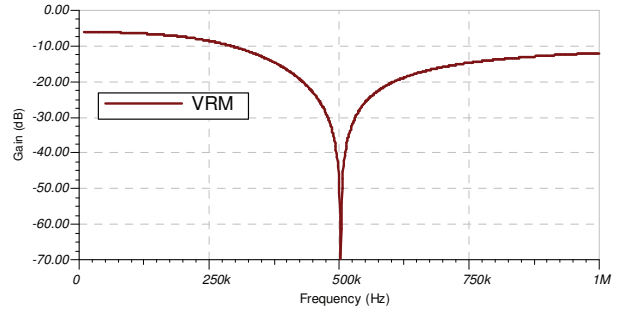
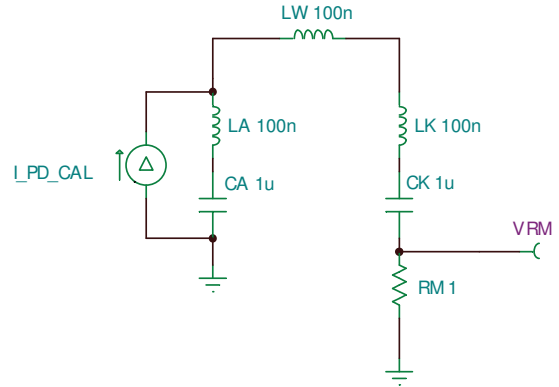


Figure 4: IEC test setup with capacitor model (top) and corresponding frequency response (bottom).

Equation 9 describes a first order system with a single pole and zero. For frequencies well above the pole frequency, i.e.

$$f \gg \frac{R_M}{2 \cdot \pi \cdot (L_A + L_K + L_W)}$$

Equation 9 can be simplified as follows:

$$\frac{I_{R_M}}{I_{\text{PD_CAL}}} = \frac{L_A}{L_A + L_K + L_W} = \frac{q_M}{q_A} \quad (10)$$

Hence, for frequencies above the resonance frequency of the test object the PD sensitivity factor, i.e. the ratio of the measured charge to the injected charge, is exclusively defined by the circuit inductances.

The equivalent PD sensitivity for the standard IEC test setup based on C_A and C_K (as described e.g. in [3], Equation 2) can be expressed as:

$$\frac{q_M}{q_A} = \frac{C_K}{C_A + C_K} \quad (11)$$

Equations 10 and 11 implicate the measured charge q_M is proportional to the injected charge q_A as long as the measurement frequency band is selected significantly below or significantly above the resonance frequency of the test object capacitor. The PD sensitivity in the inductive region

of the capacitor frequency response (i.e. $f > f_R$) is lower than in the capacitive region (see Figure 4, bottom). This effect is caused by the wiring inductance L_W , which cannot be neglected and is usually equal to or larger than L_A .

Figures 5 and 6 further illustrate the high pass and low pass filtering effects due to the measuring impedance R_M .

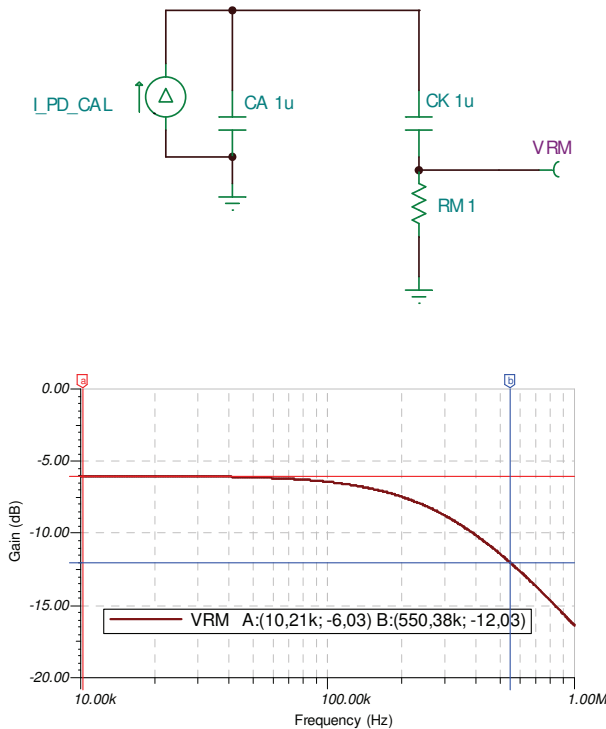


Figure 5: IEC test setup below resonance (top) and corresponding frequency response (bottom).

When measuring below the resonance frequency f_R a lower R_M value is beneficial to increasing the measurement BW. When measuring above the resonance frequency f_R a lower R_M value is beneficial to flatten the signal spectrum in the lower frequency range.

Finally, to improve the q_M/q_A sensitivity factor, the wiring must be as short as possible and the value of the measuring impedance R_M should be maintained low. Using bridge connections is detrimental to these goals since they increase the wiring length (and thus L_W) and at the same time the equivalent R_M value is doubled (because two measuring impedances are connected in series).

3 EXPERIMENTAL EXAMPLES

3.1 Below resonance frequency

The given test setup in this example, allows to set the PD filter band below the capacitor resonance frequency and simultaneously fulfil the IEC requirements for the limit frequencies of the PD filter. In Figure 7, the black capacitor on the right

hand side is the test object (a 4.4 μ F-440V film capacitor), the black capacitor on the left hand side is the coupling capacitor. The PD calibrator connectors are directly applied across the test object using crocodile clamps. The large clamp in the lower left of the figure is used for ground connection and two metal bars are employed for reduced wiring inductance L_W .

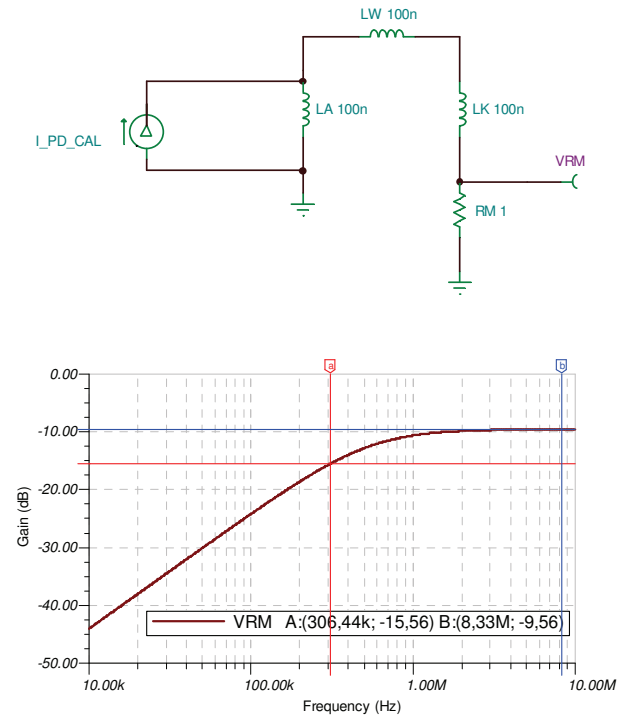


Figure 6: IEC test setup above resonance (top) and corresponding frequency response (bottom).

The frequency response in Figure 7 (bottom) indicates a resonance frequency of about 340 kHz and one can clearly recognize that the spectrum level (and hence sensitivity) is higher below than above resonance. This is in good agreement with the simulation results from Figure 4.

3.2 Above resonance frequency

In the given example setup of Figure 8 it is impossible to set the PD filter band below the resonance frequency, because there is no flat area in that part of the spectrum. Therefore, the PD filter band is set above the resonance frequency of the test object (a 30 μ F-350V film capacitor). Even though the measurement does not perfectly comply with the IEC requirements (because the lower limit frequency f_1 is set to 250 kHz) the measurement still fulfills the requirements for quasi-integration of the PD pulse.

Taking this into consideration it would make sense for the IEC standard to specify a range for BW and center frequency of the PD filter but to abandon a maximum limit for the lower limit frequency f_1 .

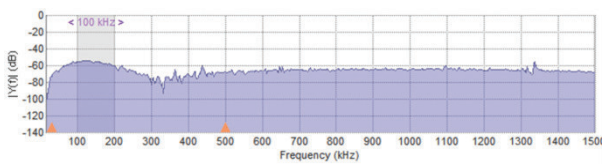
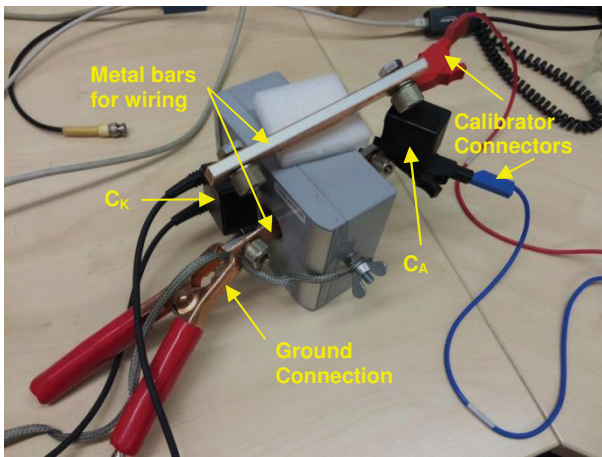


Figure 7: 4.4µF-440V capacitor measurement setup (top) and measured frequency response of the PD calibrator pulse (bottom).

The requirements for PD spectrum/filter settings developed in this paper would be a good enhancement of the IEC standard. Keeping the lower limit frequency at $f_1 \leq 100$ kHz is particularly important e.g. for transformers as covered in [6]. The PD calibration procedure is still performed according to IEC 60270 [1] with the benefit that the PD calibrator allows the verification of the PD spectrum of the test setup.

The frequency response in Figure 8 (bottom) indicates a resonance frequency of about 160 kHz and again one can clearly recognize that the spectrum level is higher below than above resonance as previously observed in Figure 7. In case of (power) capacitor testing it is utterly important to connect the calibrator leads directly across the capacitor terminals. Including parasitic wiring during the PD calibration process can easily lead to calibration errors in excess of 50%.

4 CONCLUSION

The critical aspects of PD pulse spectrum and filter settings to fulfil the quasi-integration requirements for PD measurement of power capacitors have been analyzed. In addition, the limitations due to the capacitor resonance frequency have been investigated.

It has been demonstrated that a rectangular pulse is useful to check correct quasi-integration and that the measured spectrum is a powerful tool when measuring power capacitors.

Using a swept frequency analysis the validity of PD measurement beyond the capacitor resonance

frequency has been demonstrated with corresponding measurement examples.

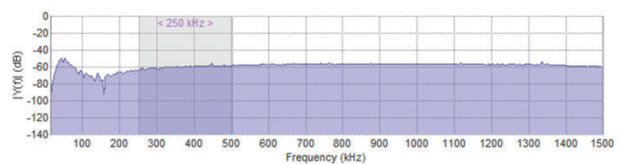
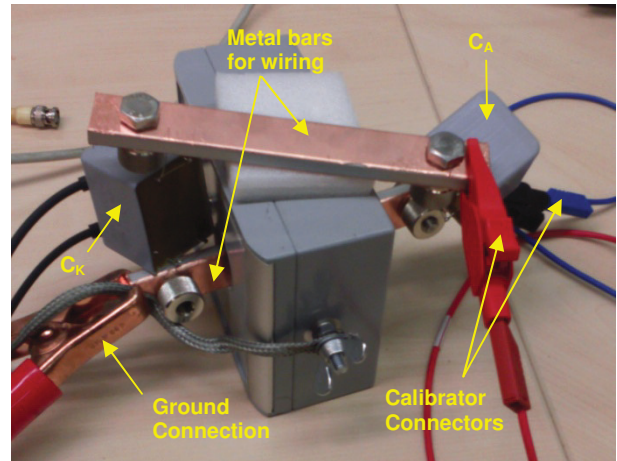


Figure 8: 30µF-350V capacitor measurement setup (top) and measured frequency response of the PD calibrator pulse.

Furthermore, a comparison of the measurement sensitivity below and above the resonance frequency of the test object has been conducted and the limitation of bridge connections has been explained.

Part of the presented discussion can be adapted to other types of test objects to check and verify correct PD pulse integration.



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
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