Off-line PD testing at various frequencies

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Current and voltage – our passion

Basic PD test circuit

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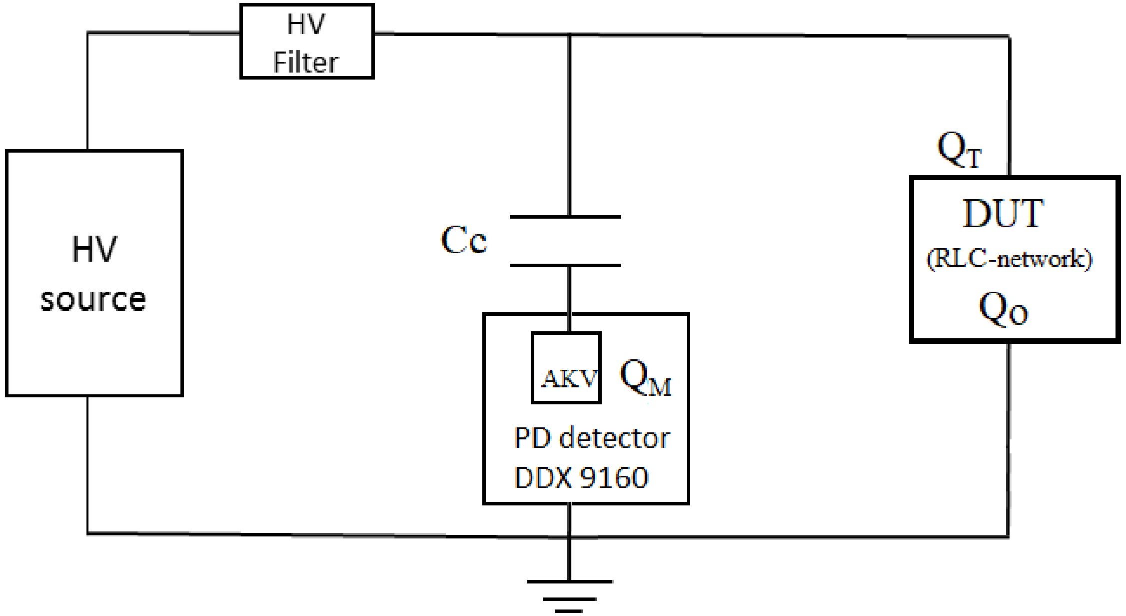

1960s

30 kHz $\le f_1 \le$ 100 kHz

$f_2 \le$ 500 kHz

30 kHz $\le \Delta f \le$ 400 kHz

Year 2015

30 kHz $\le f_1 \le$ 100 kHz

$f_2 \le$ ~~500 kHz~~ 1 MHz

30 kHz $\le \Delta f \le$ ~~400~~ 900 kHz

Stray capacitance schematic

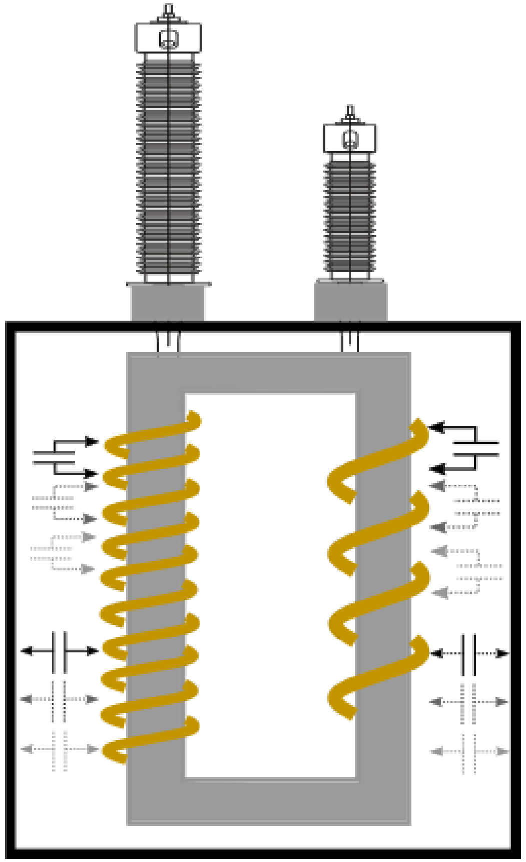

Figure 1: The stray capacitances in a transformer

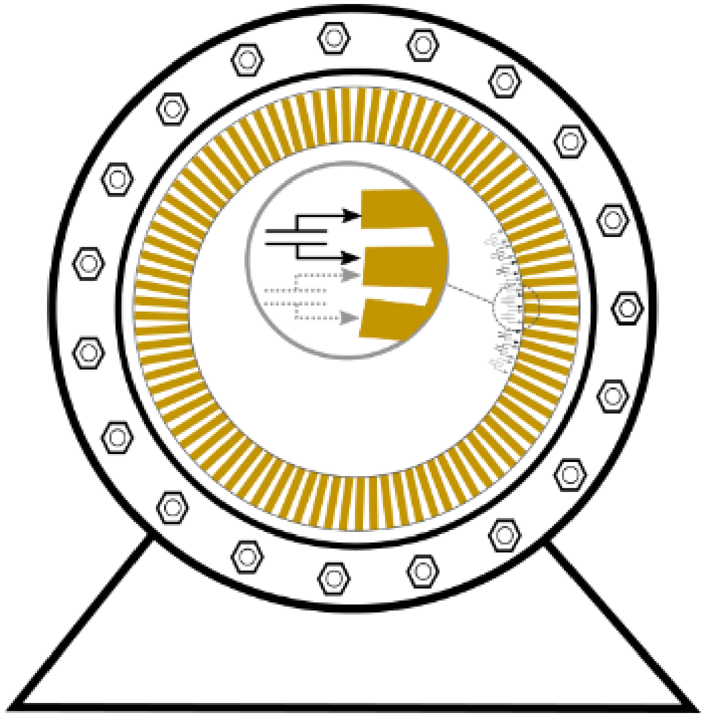

Figure 2: The stray capacitances in a rotating machines stator winding

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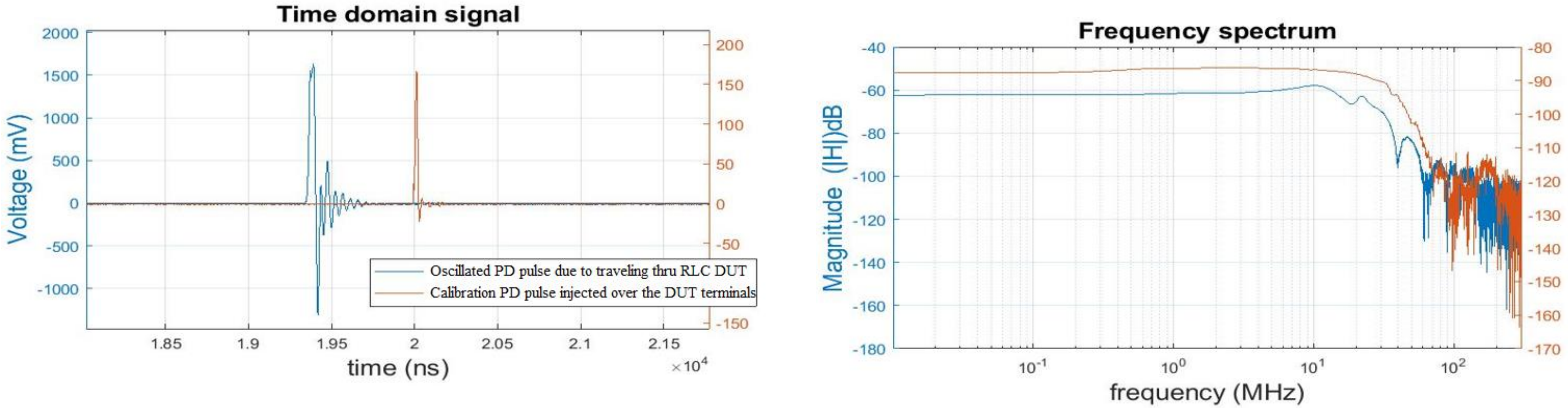

Figure: Time domain (left) and frequency domain (right) representation of two PD pulses.

Frequency spectrum analysis

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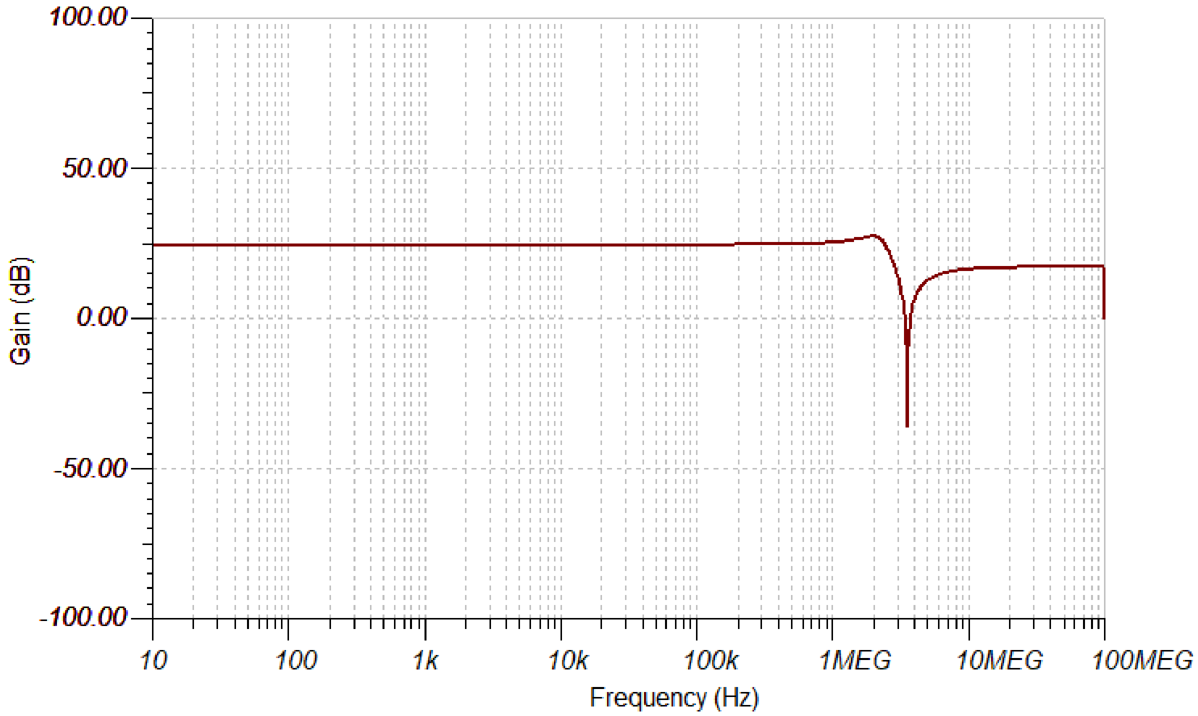
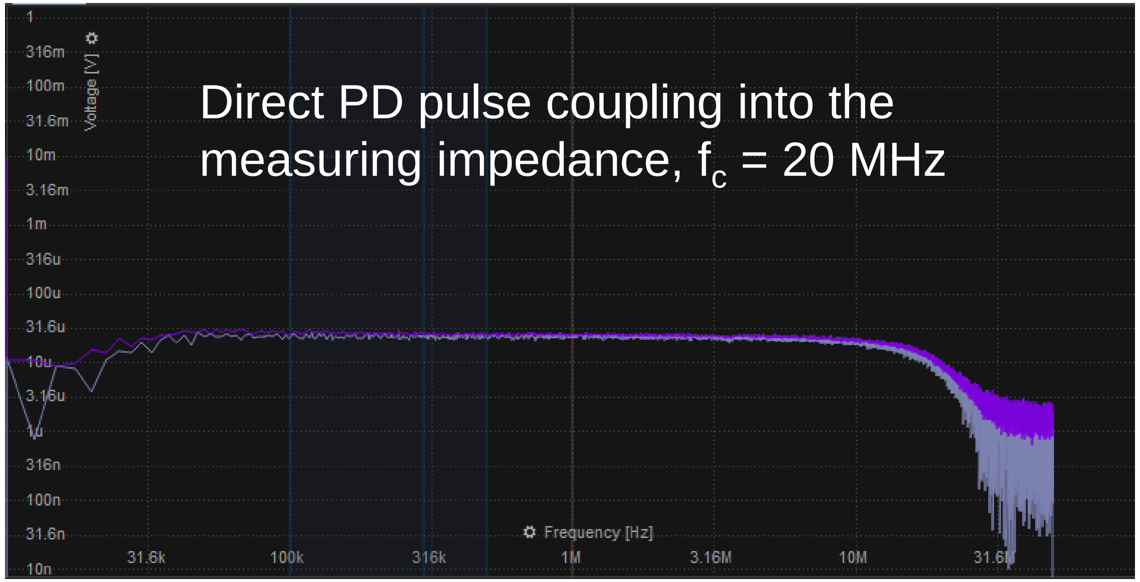
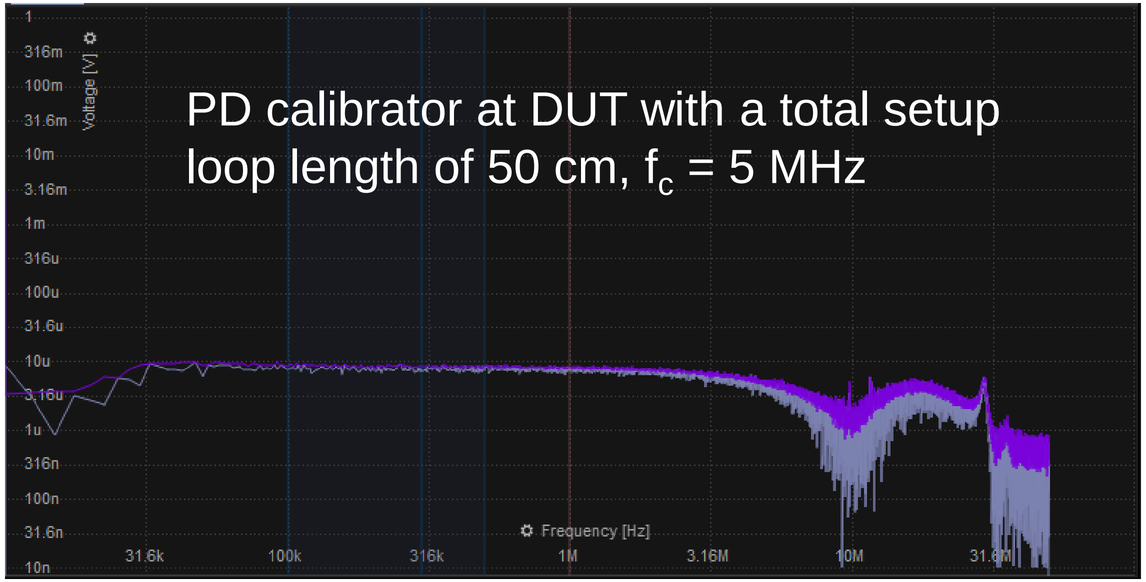
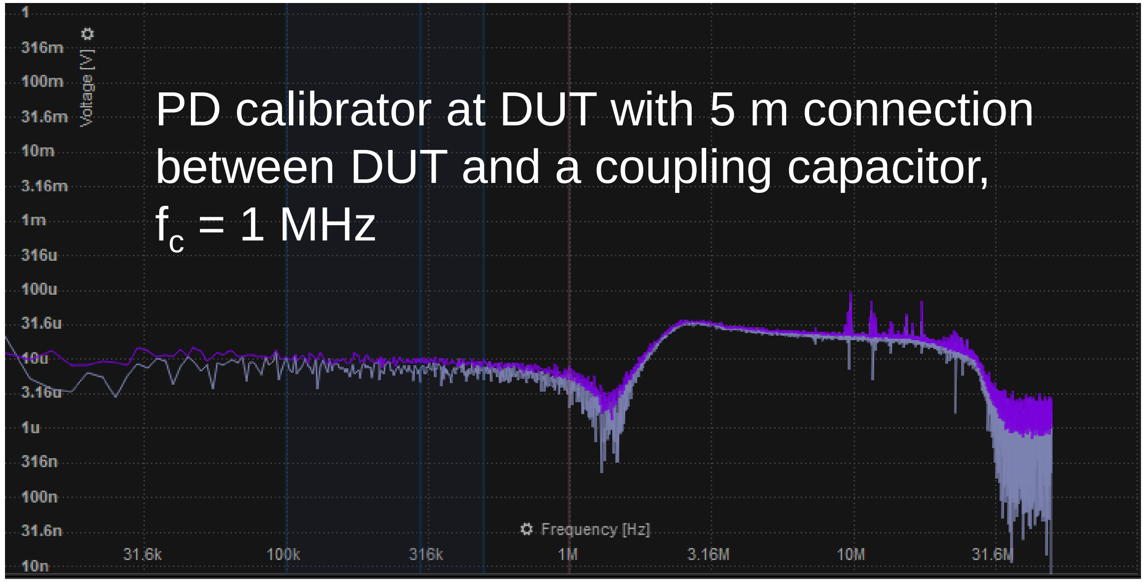


Figure: Transfer impedance of the complete PD circuit with C_c = 1 nF, C_{DUT} = 2 nF, 1 uH in series with the capacitors, and 5 uH between C_c and C_{DUT}.

Frequency spectrum analysis

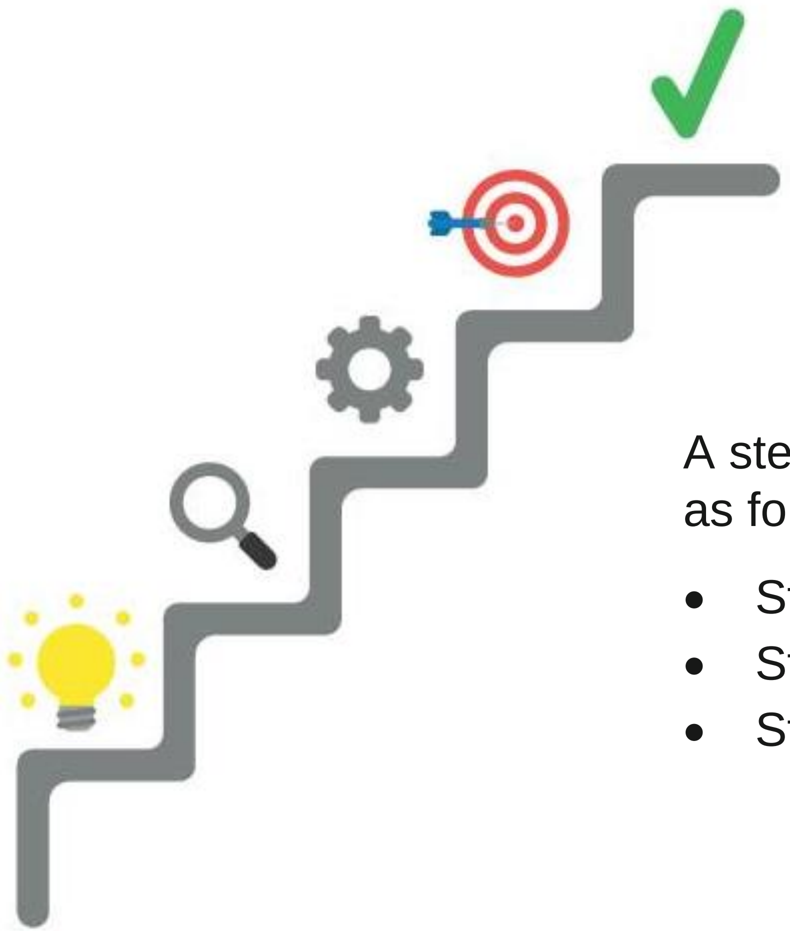






The frequency spectrums of the 100 pC calibration pulse.

Step-by-step guideline for PD measurements



A step-by-step guideline for PD measurements is outlined as follows:

- Step 1: Checking the noise spectrum
- Step 2: Checking the calibration spectrum
- Step 3: Analysing the real PD pulse spectrum

Spectrum/FFT of calibration and real PD pulse

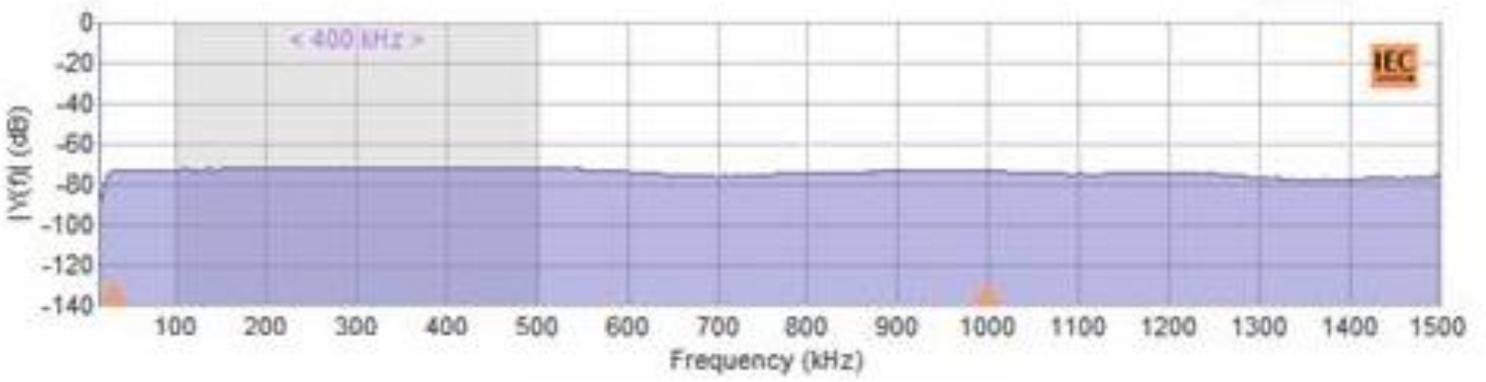


Figure 1: of the PD calibration pulse

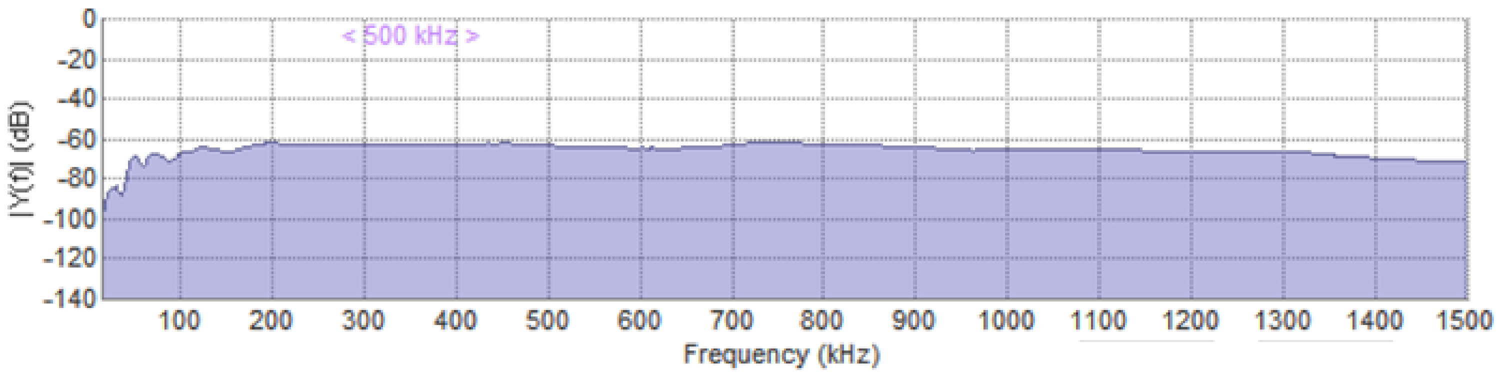


Figure 2: Spectrum/FFT of the real PD pulse

Step 3: Analyzing the real PD pulse spectrum

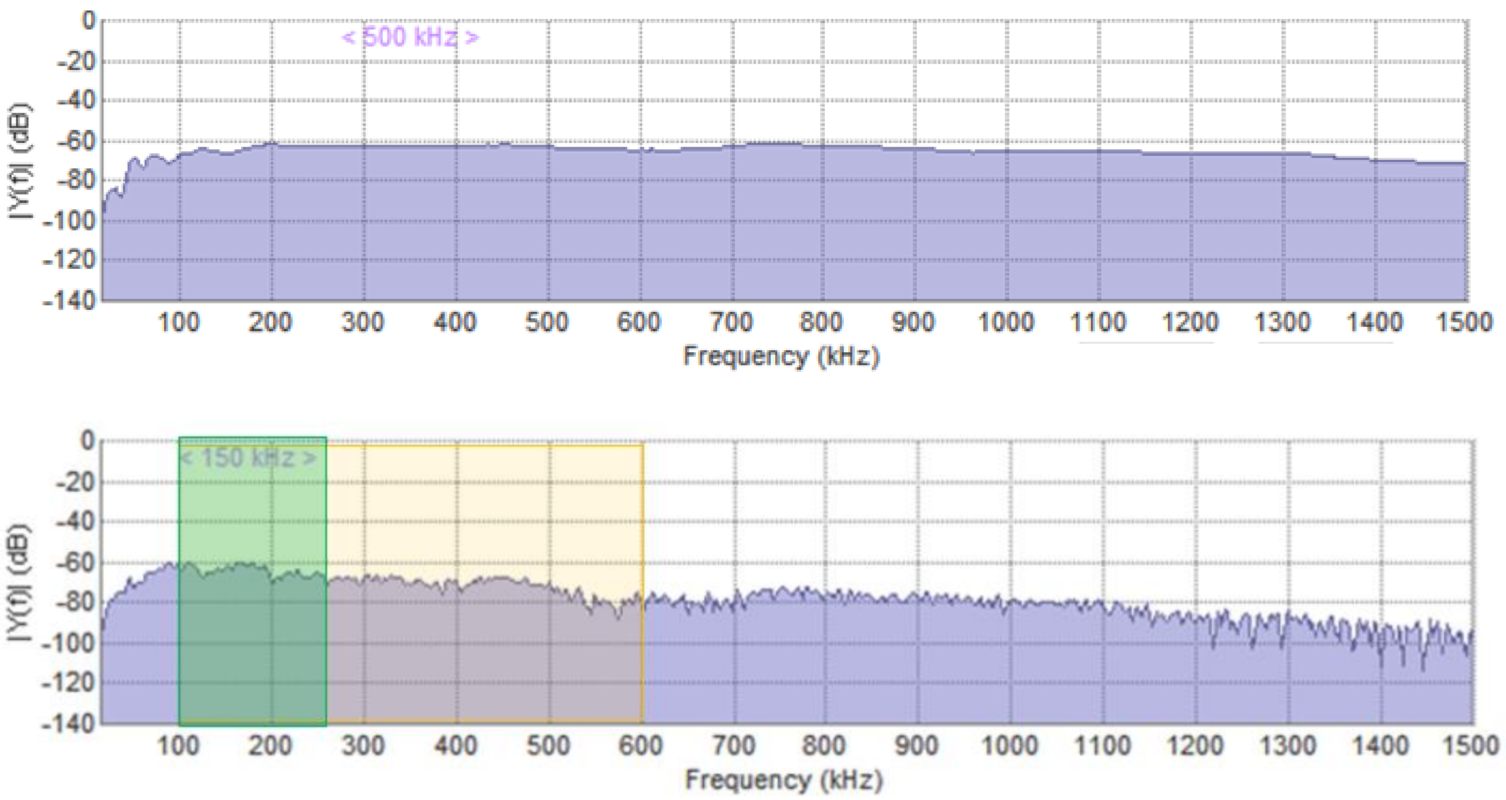
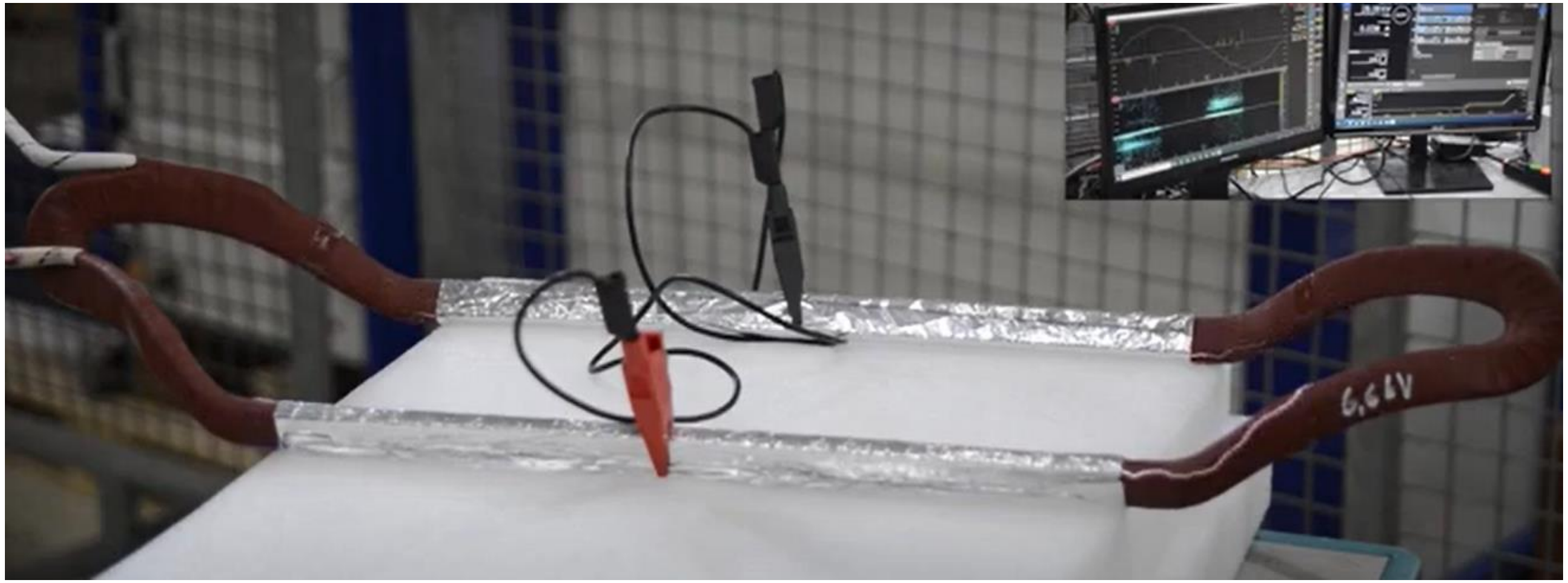


Figure 1: The calibration pulse spectrum (top) and spectrum of the real PD (bottom) measured on a stator winding

Practical verification

- DUT: stator coil of a 6.6 kV, 700 kW motor with a total coil loop length of 2 m (end-to-end) with 3 turns.



Practical verification

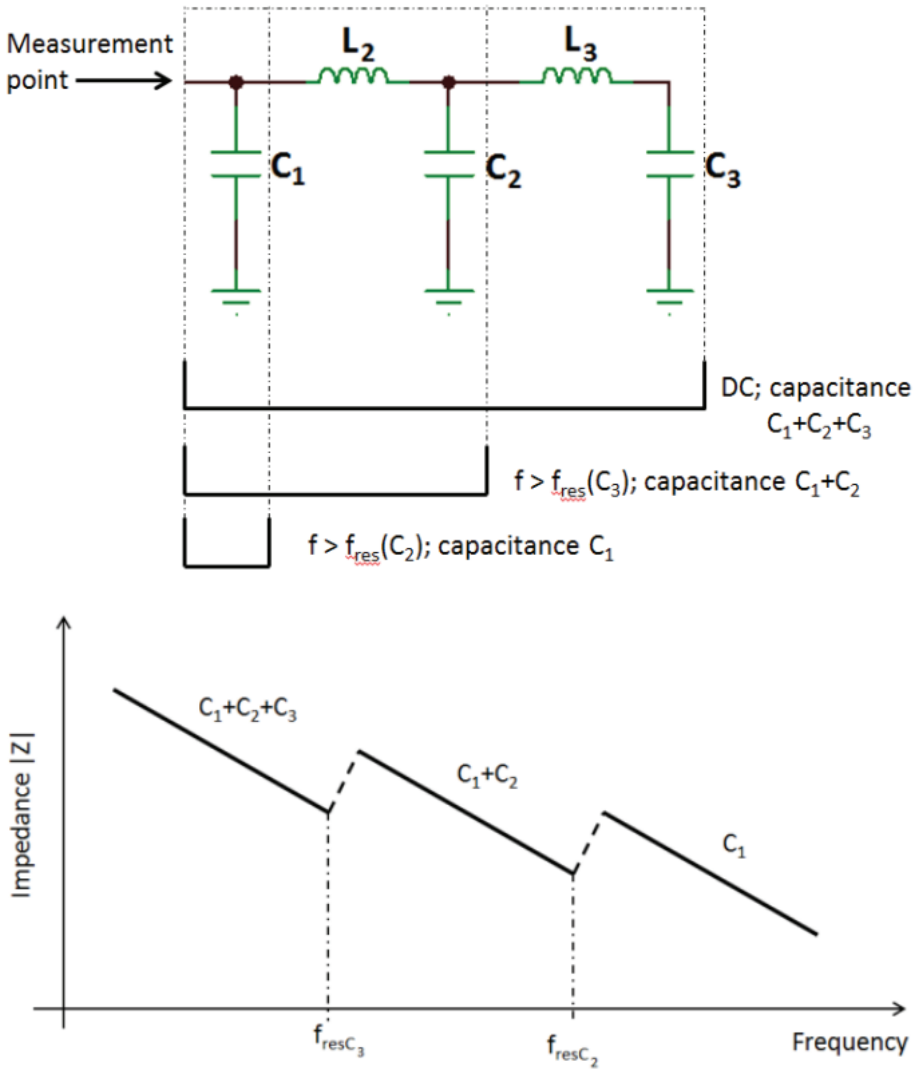


Figure: Simplified equivalent LC circuit (top) and corresponding qualitative frequency response (bottom) of e.g. a stator coil or transformer winding

Practical verification

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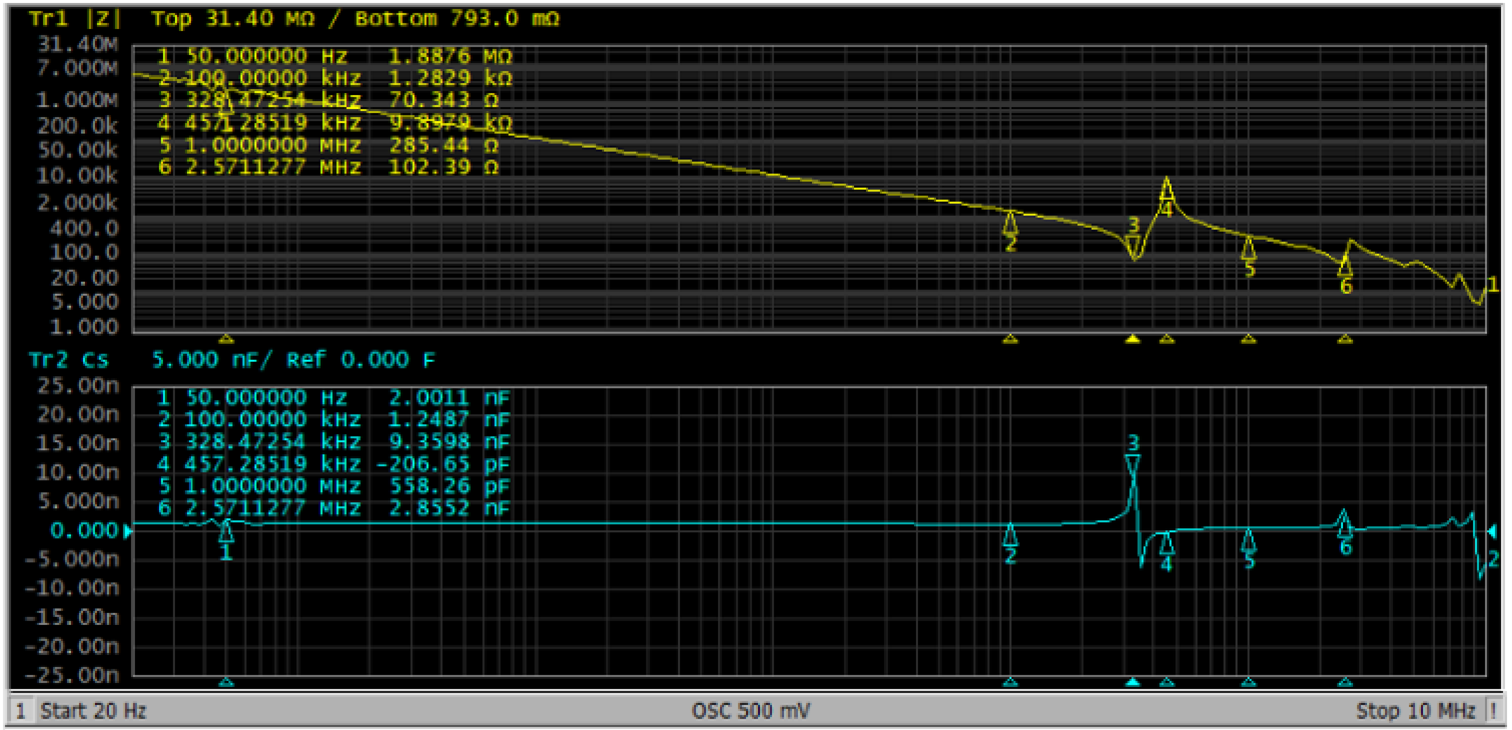
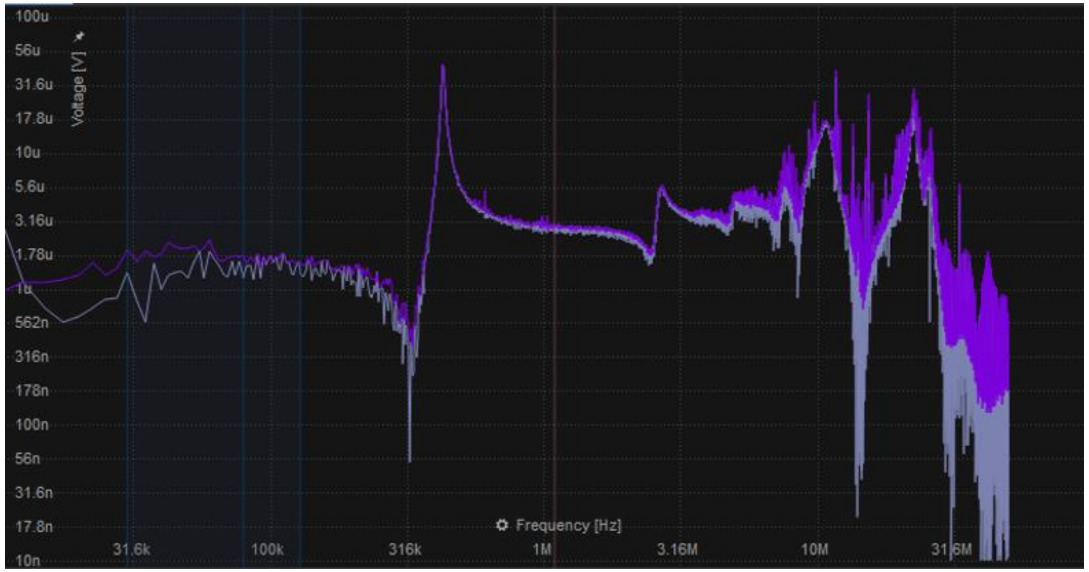


Figure: Transfer impedance Z(f) (top) and capacitance curve C(f) (bottom) of the 6.6 kV stator coil. Note the resonance and the capacitance drop.

Practical verification

Table 1 Near-end versus far-end calibration using a 100 pC calibration pulse, where near-end calibration was considered as the reference.

Calibrator @	**30 – 130 kHz**	**100 – 500 kHz**
Near-end	102 pC	99 pC
Far-end	111 pC	228 pC



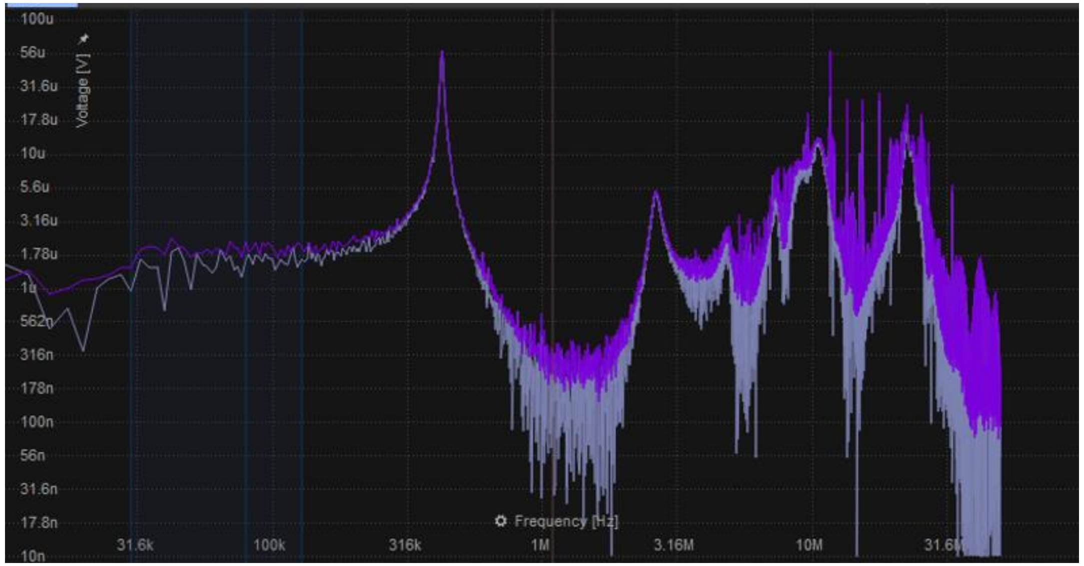


Figure: FFT of the PD calibration pulse at the near end (left) and far end (right) of the 6.6 kV stator coil.

Practical verification

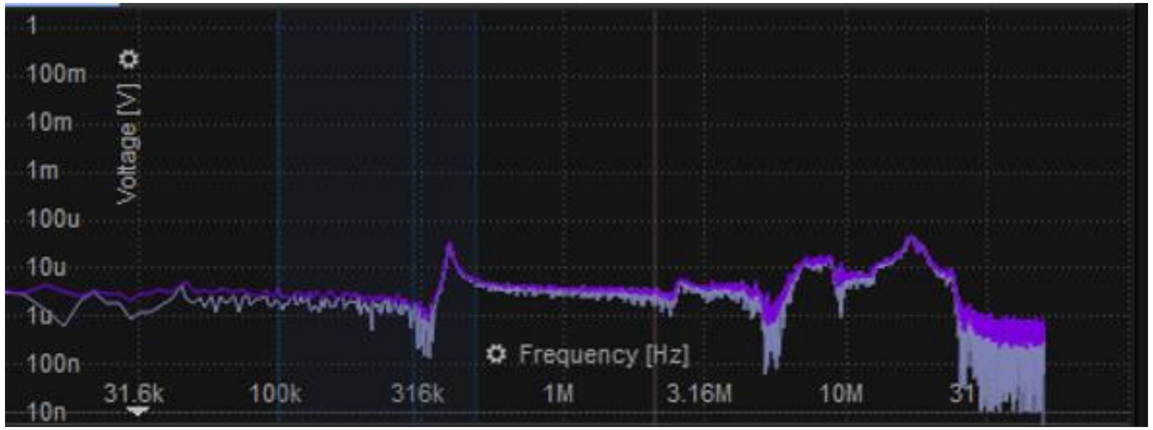


Figure: FFT of the PD calibration at 6.6 kV stator coil in the shielded room

Table PD calibration of the 6.6 kV stator coil.

Frequency Range (kHz)	**Cal. Factor**
100 – 280	14.566
100 – 500	8.397
500 – 2 000	8.494
3 000 – 4 000	6.491
7 000 – 8 800	1.804
16 500 – 18 000	0.552

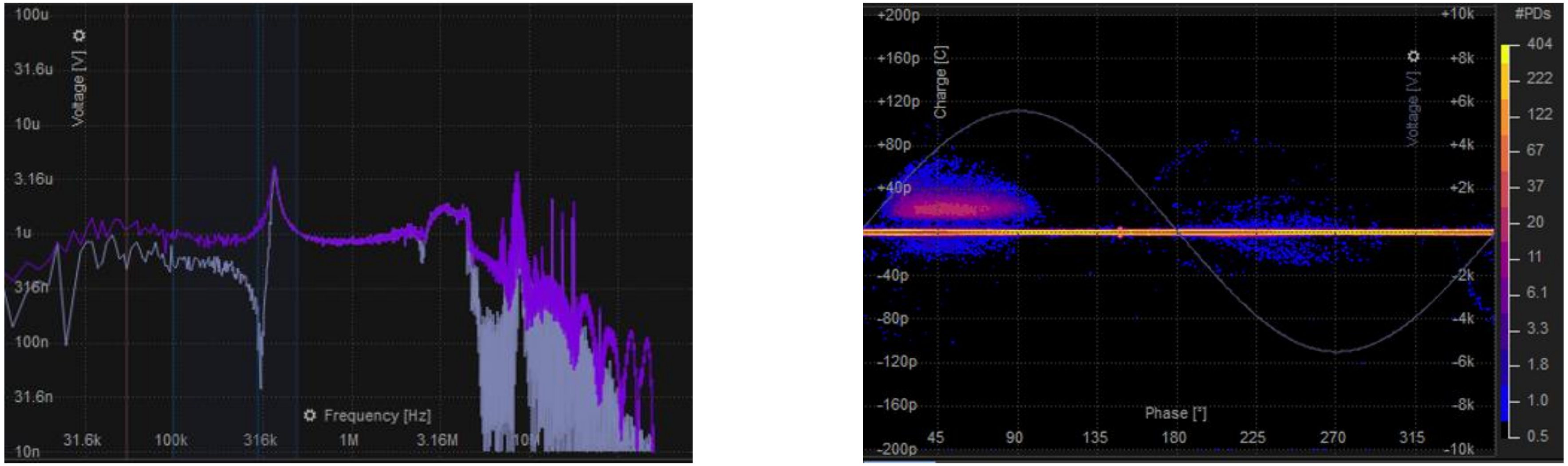


Figure 1: 6.6 kV stator coil, PD Source 1 @ 4.2 kV, PRPD pattern @ 100 – 280 kHz (right), FFT spectrum of the PD pulse (left).

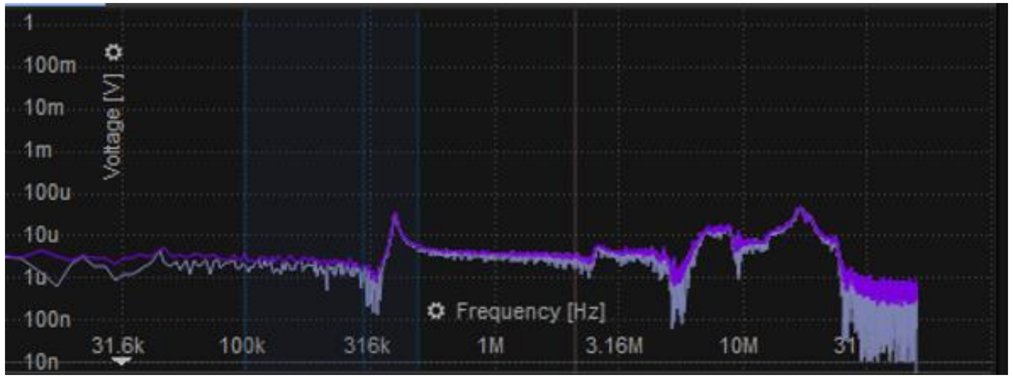
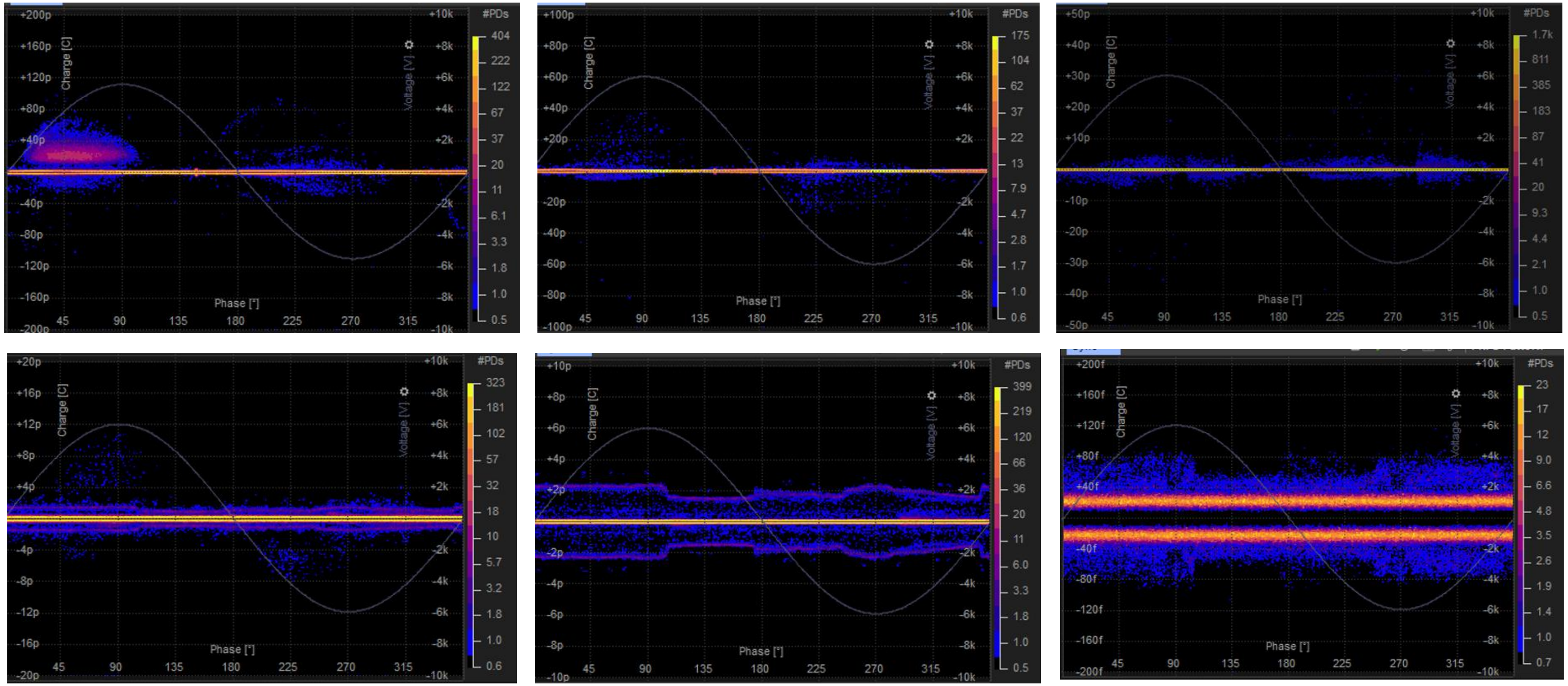
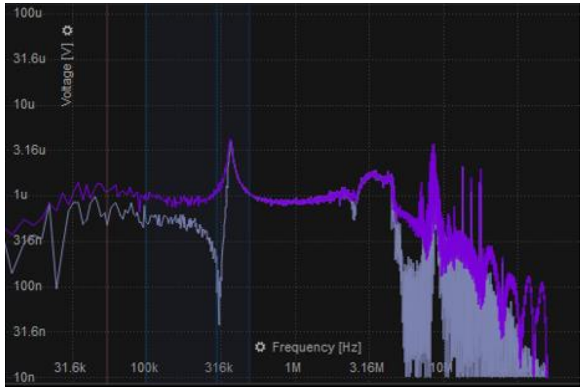


Figure 2: FFT of the PD calibration at 6.6 kV stator coil

Practical verification

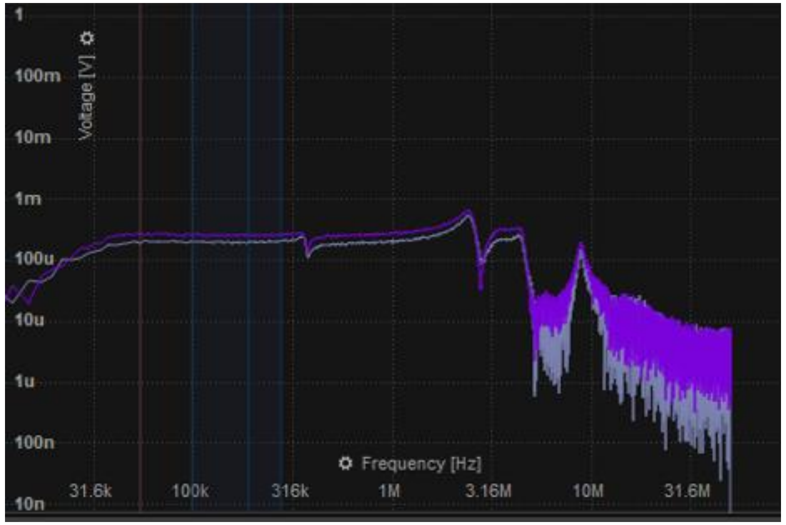




Frequency Range (kHz)	Cal. Factor	PD Source 1 @ 4.2 kV
100 – 280	14.566	40 pC
100 – 500	8.397	17 pC
500 – 2 000	8.494	7. 5 pC
3 000 – 4 000	6.491	19.7 pC
7 000 – 8 800	1.804	2.37 pC
16 500 – 18 000	0.552	0.08 pC

Top line, left to right: 100 – 280 kHz, 100 – 500 kHz, 500 – 2 MHz

Bottom line, left to right: 3 MHz – 4 MHz, 7 MHz – 8 MHz, 16.5 MHz – 18 MHz



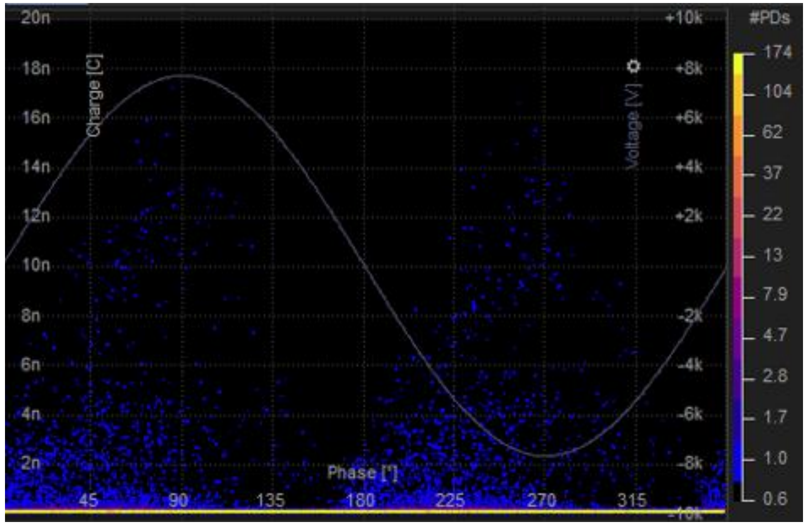


Figure 1: 6.6 kV stator coil, PD Source 1+2 @ 5.4 kV, PRPD pattern @ 100 – 280 kHz (top), FFT of the PD pulse (bottom).

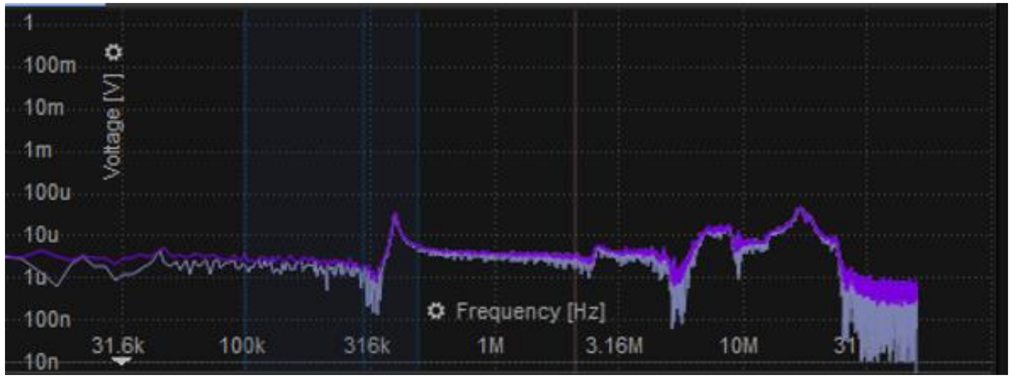
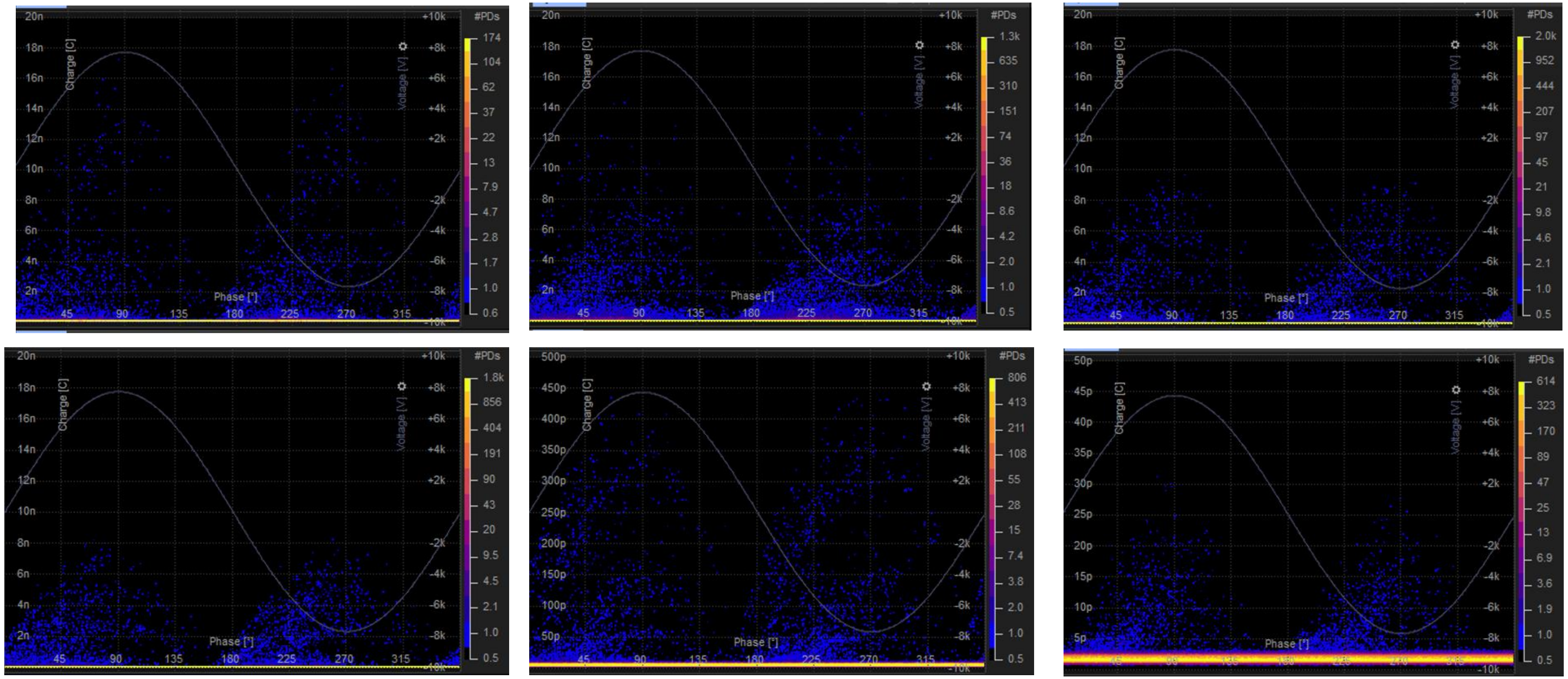
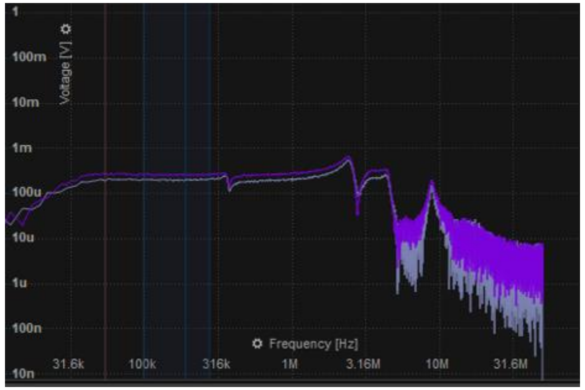


Figure 2: FFT of the PD calibration at 6.6 kV stator coil

Practical verification





Frequency Range (kHz)	Cal. Factor	PD Source 1+2 @ 5.4 kV
100 – 280	14.566	10.5 nC
100 – 500	8.397	5.36 nC
500 – 2 000	8.494	6.31 nC
3 000 – 4 000	6.491	4.94 nC
7 000 – 8 800	1.804	0.28 nC
16 500 – 18 000	0.552	0.014 nC

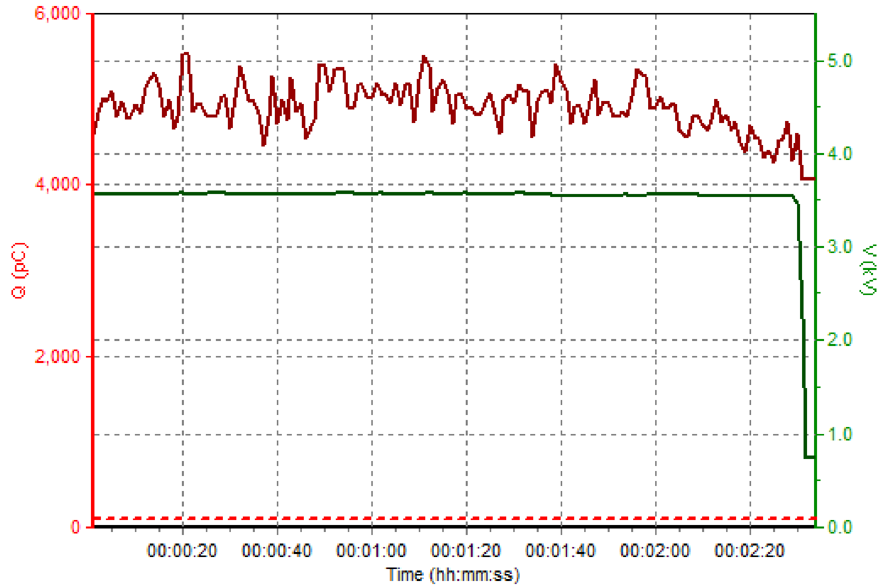
Top line, left to right: 100 – 280 kHz, 100 – 500 kHz, 500 – 2 MHz

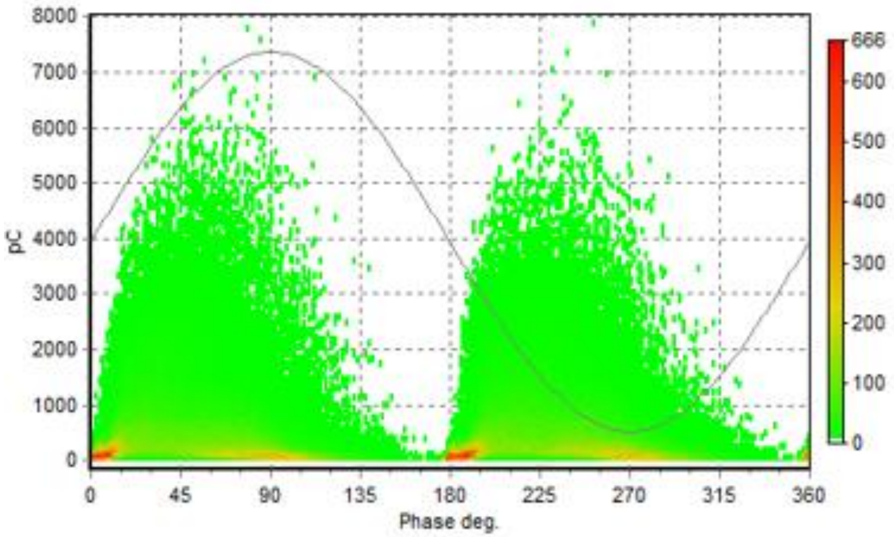
Bottom line, left to right: 3 MHz – 4 MHz, 7 MHz – 8 MHz, 16.5 MHz – 18 MHz

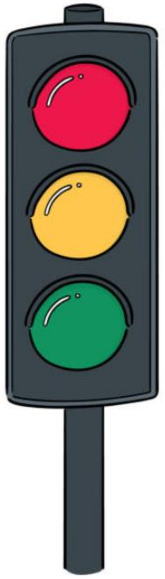
Differences using various frequency ranges

Stator (3-phase motor), Helmke, 6 kV, 600 kW, Phase A

Measuring Frequency Range: 100 – 600 kHz







> 10 nC

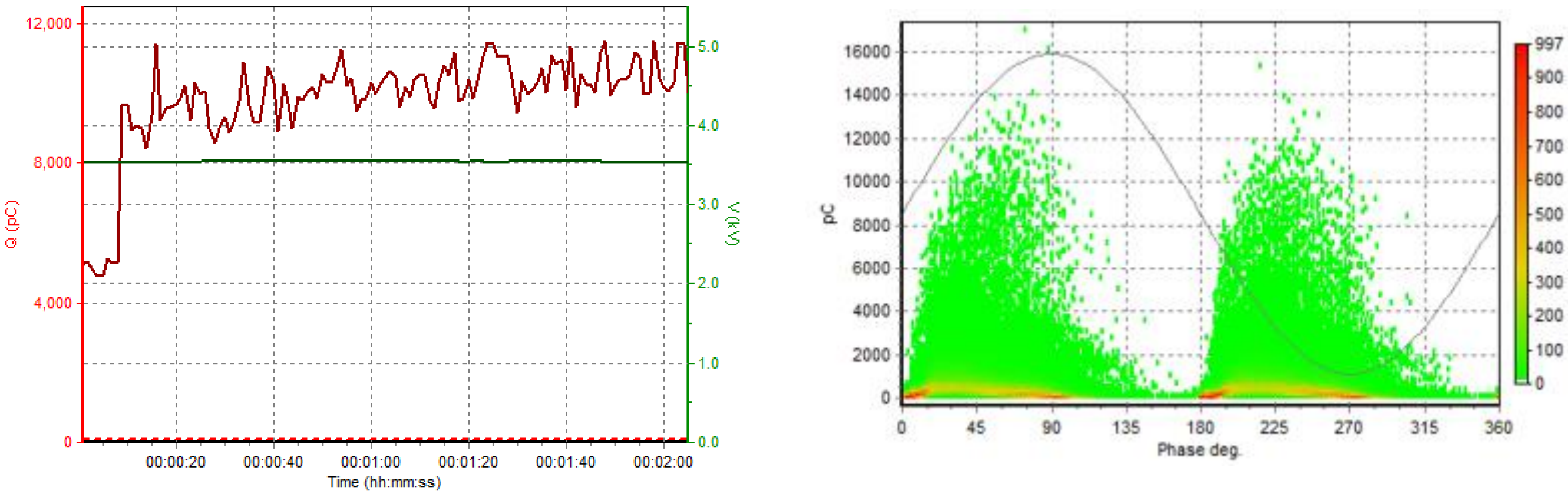
5 – 10 nC

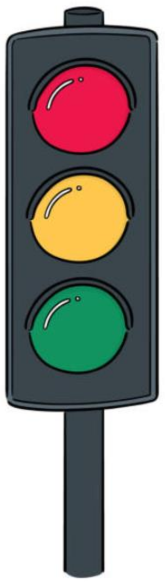
< 5 nC

Figure 1: Q_{avg} = 5000 pC, PRPD pattern peak-avg = 7000 pC

Stator (3-phase motor), Helmke, 6 kV, 600 kW, Phase A

Measuring Frequency Range: 100 – 250 kHz





> 10 nC

5 – 10 nC

< 5 nC

Figure 2: Q_{avg} = 10000 pC, PRPD pattern peak-avg = 14000 pC

Analyzing the real PD pulse spectrum

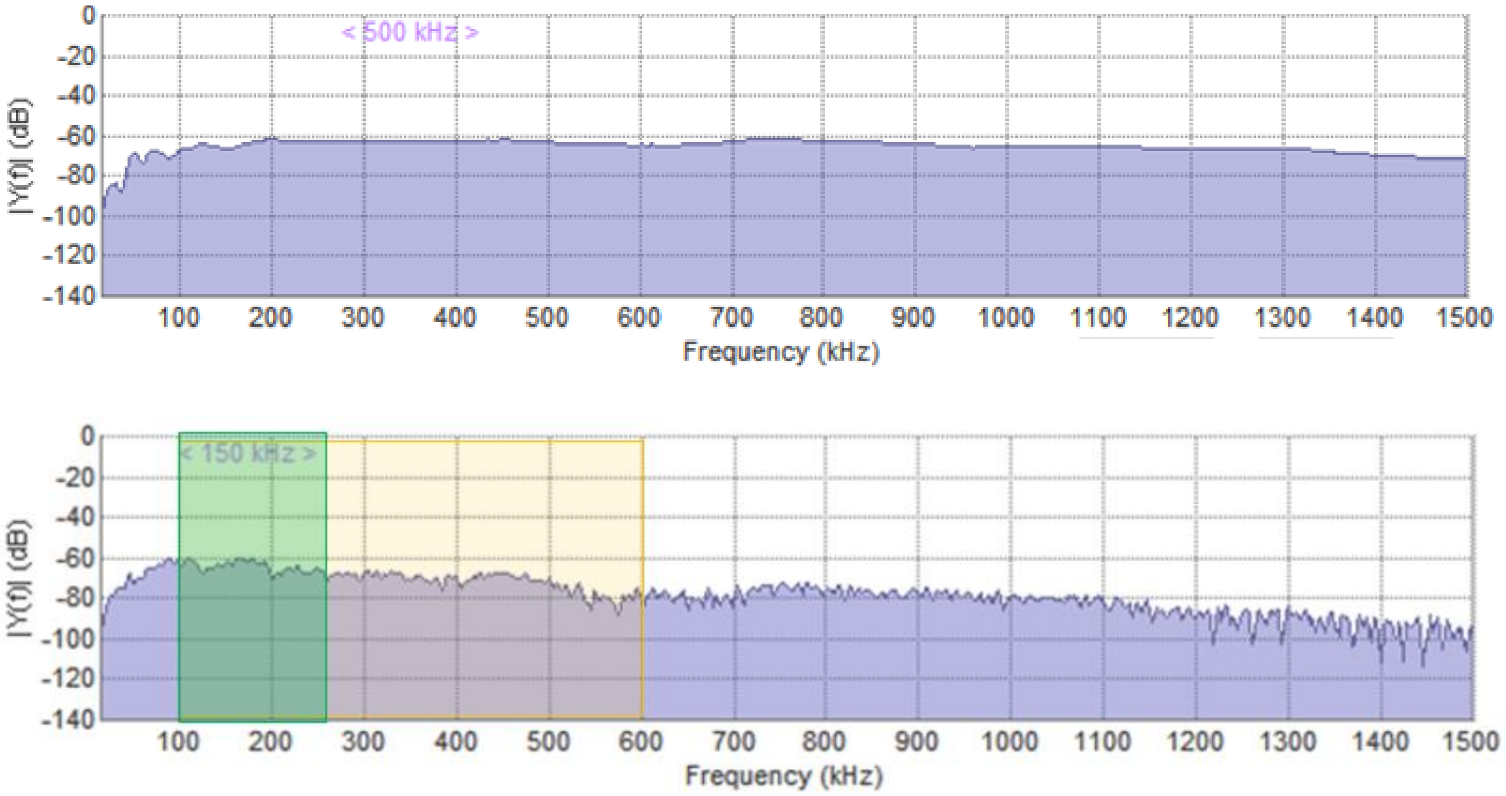
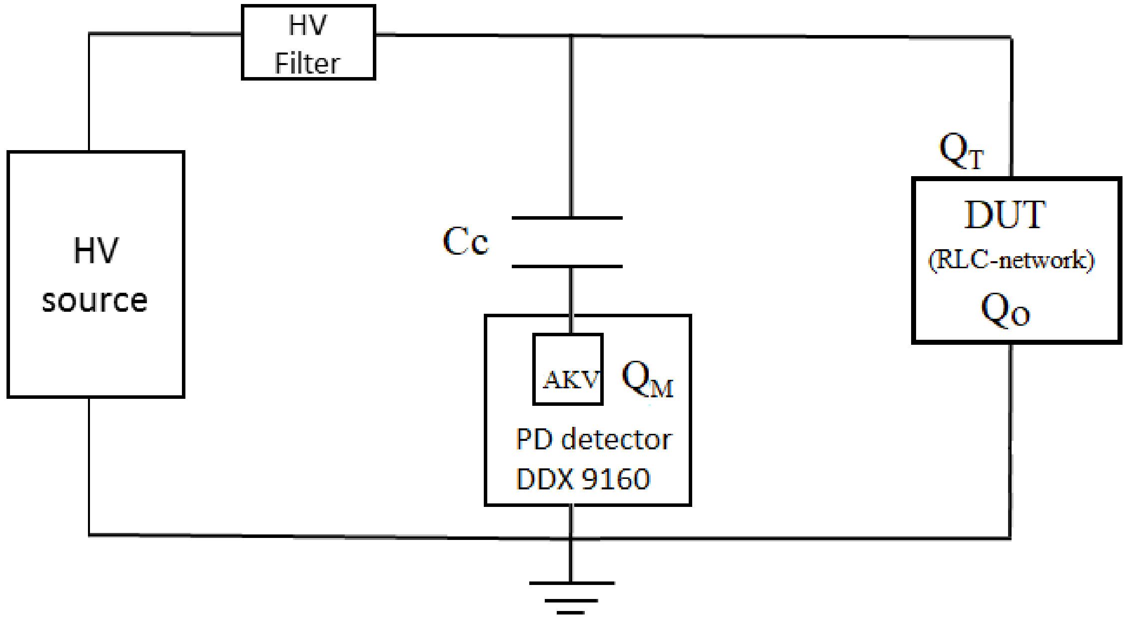


Figure 1: The calibration pulse spectrum (top) and spectrum of the real PD (bottom) measured on a stator winding

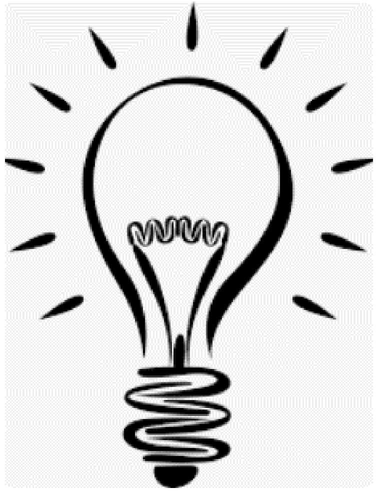
Discussion



- Term “induced” rather than “apparent” charge
- Direct relation between the charge at the PD origin Q_O and the charge at the DUT terminals Q_T
- Charge transfer between the DUT terminals and the coupling capacitor is ensured by the PD calibration process.
- The ratio between the charge Q_T and the so-called measured charge Q_M at the measuring impedance is a measure of the sensitivity defined by the following relation: $\uparrow C_c$ and $\downarrow C_{DUT}$ results in $\uparrow$SNR.

Conclusions

- Checking the frequency domain of the PD measurement
- Setting the proper measuring frequency
- IEC 60270 highlights that for large test objects and test objects with windings the upper cut-off frequency f_2 shall be kept as low as possible
- PD measurement at higher frequencies is possible, but the quantification becomes difficult
- PD sources located further from the coupling capacitor tend to be omitted and the overall measurement plausibility becomes questionable
- Term «PD indication» rather than «PD measurement»



- IEC 60270, chapter 4.3.4 Wide-band PD instruments

$$30\ \text{kHz} \le f_1 \le 100\ \text{kHz};$$

$$f_2 \le 1\ \text{MHz};$$

$$100\ \text{kHz} \le \Delta f \le 900\ \text{kHz}.$$

NOTE 2 For test objects with windings like transformers and electrical machines the acquired frequency band may be reduced down to a few 100 kHz and even below. The upper limit frequency f_2 to be accepted for such kinds of test objects should be specified by the relevant Technical Committee.

- ANSI/IEEE Std C57.12.90-2010 - IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers
- It recommends measuring in the range of 100 – 300 kHz or using even lower f_2 frequency

감사합니다 Natick

Grazie Danke Ευχαριστίες Dalu Obrigado

Thank You Köszönöm

Tack

Спасибо Dank Gracias

谢谢 Merci Seé

ありがとう