



Technical Document

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frequency response analysis for
partial discharge measurement

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INNOVATIVE APPLICATION OF FREQUENCY RESPONSE ANALYSIS FOR PARTIAL DISCHARGE MEASUREMENT

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Abstract: Measuring partial discharge on transformers and rotating machines requires knowledge of the frequency characteristics of the test object impedance. This allows assessing capacitive or transmission line behavior and localizing resonances. Impedance measurement is a helpful tool to correctly select the coupling capacitor and measuring impedance for optimal sensitivity. In this paper, a method of impedance measurement is presented based on the same frequency response analysis (FRA) equipment used for transformers. The typical decrease with frequency of the equivalent capacitance of transformers and the transmission line behavior of rotating machines are investigated both with simulations and measurements. The impedance measurement gives insight to the electrical behavior of the test object, serves to find resonances and flat sections in the spectrum and therefore provides valuable information for correct PD measurement.

1 INTRODUCTION

The sensitivity of partial discharge (PD) measurements is governed by the q_M/q_A ratio, where q_M is the measured charge and q_A is the apparent charge at the test object. This ratio is defined by the capacitance of the test object C_A and the coupling capacitor C_K as described in [1]. For increased PD measurement sensitivity C_K is preferably chosen as large as possible but in general the value of the coupling capacitor is selected between $1/10^{\text{th}}$ and one half of the test object capacitance to avoid excessive loading of the HV source.

While high PD sensitivities can be achieved for low capacitance test objects such as HV bushings or small and medium size (e.g. distribution) transformers, the situation is more difficult in the case of large power transformers and rotating machines due to their relatively high capacitance.

The capacitance of rotating machines is typically in the range from 100 nF up to 1 μ F and even higher in case of large hydro generators. However, coupling capacitor values in excess of 100 nF are unrealistic both from a physical and economical point of view.

For practical applications, the maximum value of coupling capacitors is usually in the range of 10nF to 40nF. The capacitance of transformers and rotating machines is commonly determined during dissipation factor measurements at 50 Hz. However, the capacitance varies with frequency due to resonances caused by the complex RLC nature of those devices. For this reason, it is inappropriate to derive the size of coupling capacitors based on low frequency capacitance measurements.

This paper introduces a simple measurement procedure to determine resonances and impedance characteristics of common test objects. Guidelines are given on how to estimate proper values for coupling capacitors as well as how to properly select filter bandwidth and cut-off frequencies for PD measurement.

2 FREQUENCY ANALYSIS

2.1 Transformers

The equivalent capacitance of transformers decreases with increasing frequencies which can be explained by the basic LC network shown in Figure 1. This simplified transformer model consists of the stray capacitances C_1 to C_3 which are connected by the winding inductors L_2 and L_3 . For DC, all inductors are short-circuited and the equivalent capacitance is represented by the parallel connection of C_1 , C_2 and C_3 as illustrated in Figure 1. For increasing frequencies, C_3 will be the first capacitor to enter resonance with (L_2+L_3) , being effectively disconnected for $f > f_{\text{res}}(C_3)$. For even higher frequencies a second resonance will arise due to L_2 and C_2 in parallel with part of the previous resonant network (L_2, C_3) . This resonance is roughly determined by $(L_2+L_3)/2$ and C_2 .

In essence, Figure 1 illustrates that the capacitance and impedance of the test object abruptly changes after each resonance in the LC network.

2.2 Rotating machines

The stator windings of rotating machines show similar characteristics as transformers with some specific differences. The slot part of the stator winding can be essentially described as a transmission line based on the following assumptions for a large rotating machine. The

stator bar with a typical length of 5 m results in an equivalent capacitance of 5 nF as mentioned in [2].

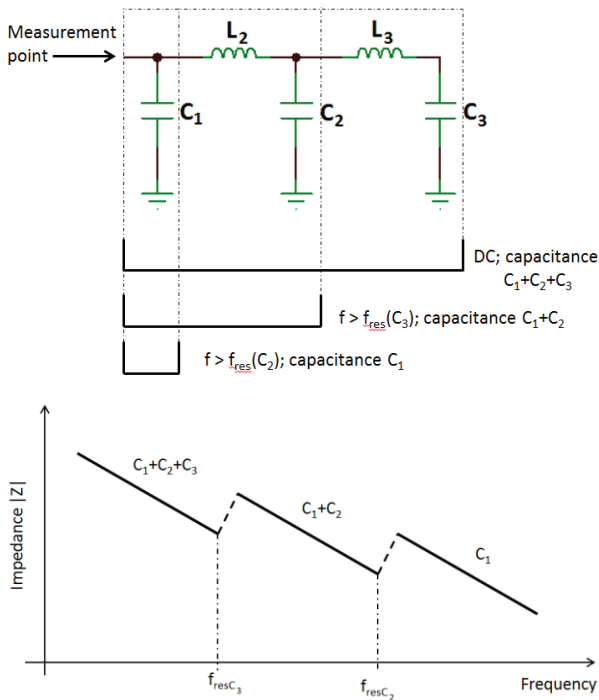


Figure 1: Simplified equivalent LC circuit for a transformer (top) and corresponding qualitative frequency response (bottom).

An equivalent total inductance of 5 μH can be derived according to the rule of thumb established in [3]. From the previous estimations the characteristic impedance of the slot part of the stator can be calculated as

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{5 \times 10^{-6}}{5 \times 10^{-9}}} \cong 30 \Omega \quad (1)$$

Outside of the slot (i.e. in the end-winding part) the characteristic impedance is not identical and the coil end-winding behaves as an inductance, with significant mutual capacitance to other coils [2]. An equivalent circuit diagram for the rotating machine and a single stator winding is shown in Figure 2.

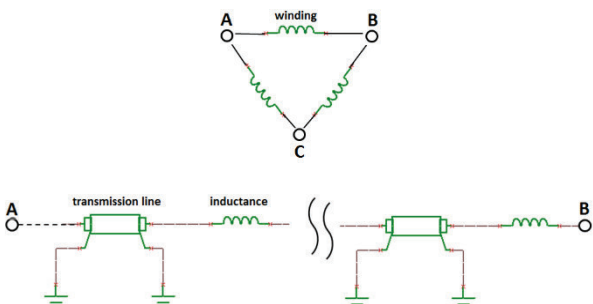


Figure 2: Equivalent circuit of a rotating machine with stator windings (top) and corresponding equivalent circuit for a single winding (bottom).

At lower frequencies the behavior of the stator bars is similar to capacitors. A decrease of capacitance with frequency can be noticed, but the effect is

much smaller because of the small inductance of the end-winding connections. However, since PD pulses are wideband pulses, it is reasonable to consider the bars as transmission lines and hence utilize a coupling impedance matching the characteristic impedance of the bars. This ensures reduced reflections, higher energy transfer and better analysis capabilities.

For stator bars, a capacitive behavior up to the first resonance frequency (defined by the sum of all inductances in the circuit and the total bar capacitance) can be observed. Additional resonances in close proximity (closer when more slots are in) occur for higher frequencies and the impedance curve oscillates along the characteristic impedance of the bars.

For the case of rotating machines, impedance measurement is particularly useful to understand the similarities with cable characteristics as shown in section 4.2. The complex distributed nature of stator windings is also covered in the corresponding international standard [4].

2.3 Impedance measurement using FRA

Impedance measurement can be theoretically performed using a Vector Network Analyzer (VNA). However, these devices are optimized for 50 Ω environments which do not comply with the large variation of impedance characteristics of electrical power apparatus such as rotating machines or transformers. Hence, VNAs are not intended for on-site measurements but are mostly used in laboratories.

To circumvent the limitations of VNAs, a new measuring technique has been developed, taking into account the advantages of a Frequency Response Analysis (FRA) device. FRA is a method to measure the frequency response of passive electrical devices (RLC) which has been originally developed to detect mechanical damages in transformers [5]. The FRA measuring device consists of a pair of source and receiver probes where the source probe transmits a swept AC voltage signal (12V or 24V, with variable frequencies from 10 Hz to 10 MHz). The receiver probe monitors the voltage signal and finally the transfer frequency characteristic is calculated as:

$$A = 20 \cdot \log\left(\frac{U_2}{U_1}\right) \quad [A] = \text{dB} \quad (2)$$

The FRA has been designed for transformer phase-to-phase measurements and hence a modified test setup is required for phase-to-ground PD measurements as shown in Figure 3.

The generator resistor R_g is connected in series with the FRA generator output. The device under test (DUT) is then connected in parallel with the receiver probe virtually creating a voltage divider. The generator resistor R_g is variable and must be

adapted to the impedance of the DUT to ensure adequate measuring sensitivity as described in Section 3.

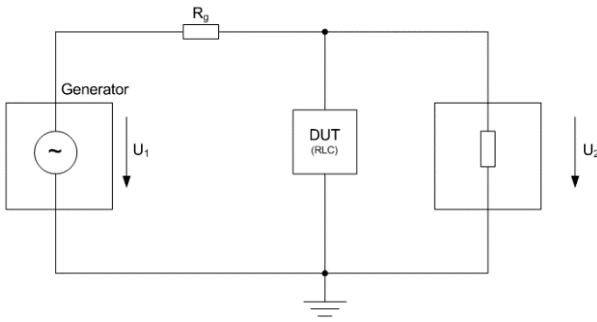


Figure 3: Modified FRA measurement test setup.

Based on the measuring circuit shown in Figure 3 the capacitance C_{DUT} of the DUT can be calculated using the following equation:

$$C_{DUT} \approx \frac{1}{2 \cdot \pi \cdot f \cdot R_g \cdot 10^{\frac{A}{20}}} \quad (3)$$

where: R_g Generator resistor
 A Attenuation in dB
 f Frequency for selected measurement point

Equation 3 is valid only in the capacitive roll-off region of the measured impedance curve.

3 SIMULATION RESULTS

The theoretical assumptions discussed in section 2 have been verified by SPICE simulations. In a first step, the impact of the generator resistor R_g to the overall measurement sensitivity of a simple LC circuit (DUT) is investigated. As shown in Figure 4 a decrease of R_g leads to increased measurement sensitivity.

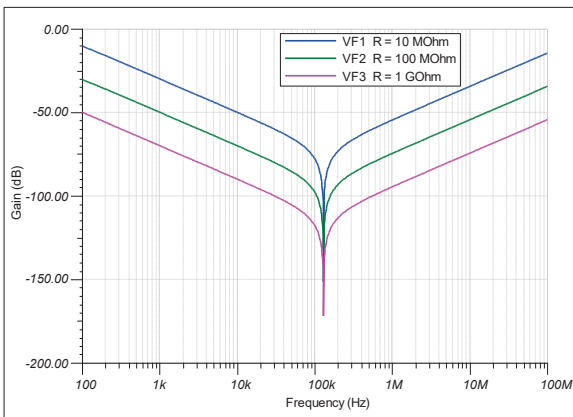


Figure 4: Frequency response of a simple LC circuit for various values of R_g .

In a second step, the variation of the frequency response for a set of RLC prototype circuits is assessed. The RLC circuits are depicted in Figure 5 (top) where the first arm (VF1) represents an RLC circuit with two resonances, the second arm (VF2) is a pure capacitor with $C = 50$ pF and finally

the third arm is an RLC circuit with a single resonance.

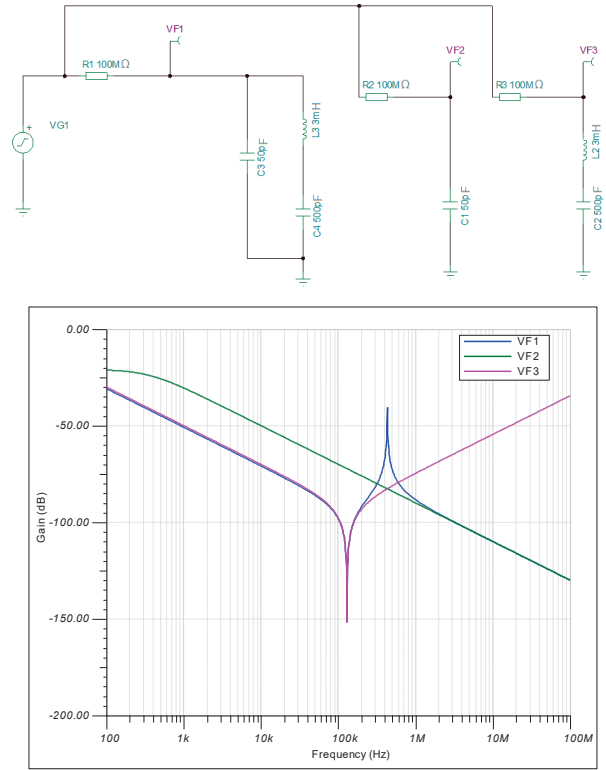


Figure 5: Variation of equivalent RLC circuits (top) and corresponding frequency response (bottom).

As shown in Figure 5 (bottom) the frequency response of the first and third arm (VF1 and VF3) overlap up to the first resonance at 130 kHz due to L_3 and C_4 (L_2 and C_2). Beyond this first resonance the response of VF3 is purely inductive while for VF1 a second resonance arises at 411 kHz due to L_3 and C_3 . Above this second resonance the frequency response of VF1 is dominated by the capacitive behavior of C_3 thus overlapping with the response of VF2 ($C_1 = C_3 = 50$ pF) starting from 1 MHz.

As an example, the upper part of the circuit diagram in Figure 6 (top) illustrates an RLC network of a simplified transformer model containing three capacitors in parallel, each with capacitance of 500 pF. The lower part of the circuit diagram contains the potential equivalent capacitances of the RLC model (500, 1000 and 1500 pF). The corresponding frequency response of the given RLC circuits is shown in Figure 6 (bottom).

Depending on the frequency range the response of the full RLC circuit (VF1) overlaps with the response of the corresponding sub-circuit (VF2 to VF4). For example, the effective capacitance at lower frequencies (50 Hz) is 1500 pF (overlapping curves VF1 and VF4). Two resonances at roughly 500 Hz and 5 kHz limit the capacitance of the test object at higher frequencies. As a consequence the equivalent capacitance of the test object in the

frequency range of 100 – 500 kHz used for PD measurements is effectively reduced to 500pF.

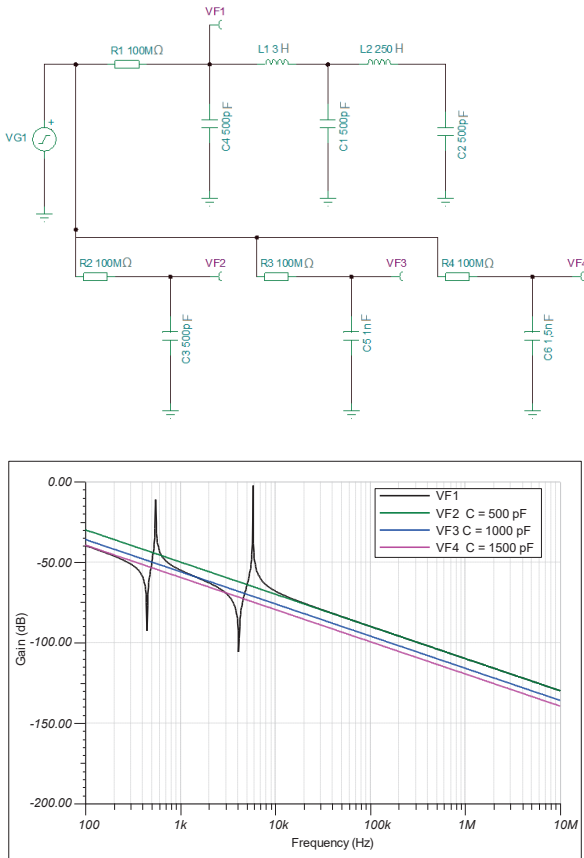


Figure 6: Example RLC network (top) and corresponding frequency response (bottom) for the determination of equivalent circuit capacitances.

4 EXPERIMENTAL RESULTS FROM ON-SITE MEASUREMENTS

To verify and highlight the advantages of the method presented in the previous sections, several measurements on real transformers and rotating machines have been conducted. All magnitudes of the impedance functions in Figures 8 – 14 are calculated according to Equation 2.

The following test procedure has been applied to the each test object:

1. Make connections according to Figure 3
2. Use variable generator resistors R_g to estimate proper sensitivity †
3. Choose the optimal R_g for best sensitivity
4. Record the impedance frequency response
5. Use a database to compare the measured response with curves for pure capacitors ‡

† The impact of R_g on the measurement sensitivity has been illustrated in Figure 4. The following values for the generator resistor have proven sufficient to cover the majority of common test object impedances: $R_g = 1$ k Ω , 10 k Ω , 100 k Ω , 1 M Ω .

‡ It is recommended to create a database of pure capacitor impedance response curves and it is important to use the same R_g value when comparing the characteristics of pure capacitors with selected test objects.

4.1 Distribution transformers

The first test object investigated is a distribution transformer with HV = 10.5 kV, LV = 400 V as shown in Figure 7.



Figure 7: Distribution transformer (HV = 10.5 kV, LV = 400 V).

The frequency response of HV phase U to ground has been measured for various generator resistors R_g . The effect of the generator resistor on the measurement sensitivity is illustrated in the curves of Figure 8 which are in good agreement with the simulation results of Figure 4.

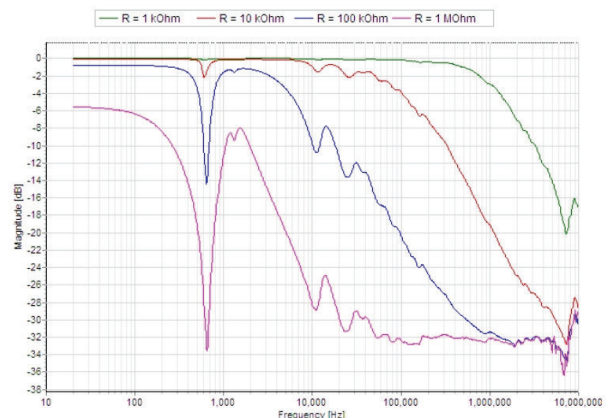


Figure 8: Impedance frequency characteristics of the 10.5/0.4 kV distribution transformer for various generator resistors R_g .

The second test object was a distribution transformer from Maschinenfabrik Oerlikon (HV = 15.5 – 16.5 kV, LV = 400 V, S = 75 kVA) whose impedance frequency characteristics are shown in Figure 9. The low frequency equivalent capacitance of the single phase U has been

measured using a Tettex MIDAS 288x instrument which includes a capacitance and $\tan \delta$ (dissipation factor) measuring bridge [6]. The measured capacitance at 50 Hz was 1.3 nF. From Figure 9 it is observed that the first resonance occurs at approximately 650 Hz. For comparison, the impedance frequency response of several capacitors has been measured by the same test procedure. In the frequency range specified for PD measurement (i.e. 100 – 500 kHz), a capacitance value in the order of 100 – 150 pF can be extracted for the given test object. Hence, the equivalent capacitance for PD measurement is approximately 10 times lower than at 50 Hz.

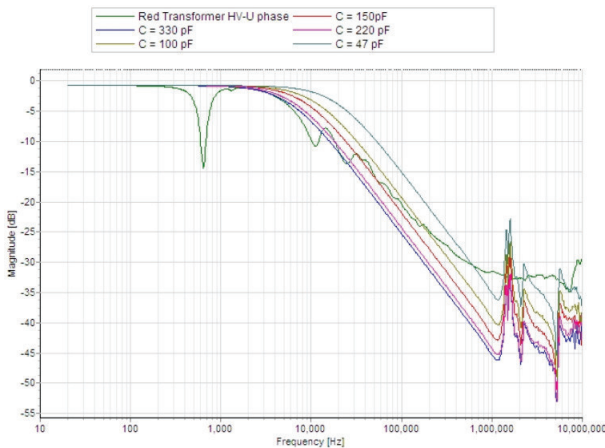


Figure 9: Impedance frequency characteristics of the distribution transformer from Maschinenfabrik Oerlikon.

Two additional distribution transformers have been characterized to verify the consistency of the test method. The first test object was manufactured by Brown Boveri (HV = 10 – 10.6 kV, LV = 400 V, S = 400 kVA) and the second one by Breda (HV = 19 – 21 kV, LV = 400 V, S = 630 kVA). Both transformers are shown in Figure 10.



Figure 10: Distribution transformers from Brown Boveri (left) and Breda (right).

Again, the reference capacitance at 50 Hz has been measured using a Tettex MIDAS 288x resulting in $C = 2$ nF and $C = 3.7$ nF for the HV

winding of the Brown Boveri and the Breda transformer, respectively.

The impedance frequency characteristics of the Brown Boveri transformer are shown in Figure 11. The low frequency capacitance derived from the impedance frequency response is approximately 2.2 nF, which proves a good correlation between both measuring techniques. At 50 kHz and beyond several closely spaced resonances occur. For this part of the response curve, the determination of the equivalent capacitance is ambiguous but a distinct decrease of the equivalent capacitance can be observed as indicated by the $C = 750$ pF curve.

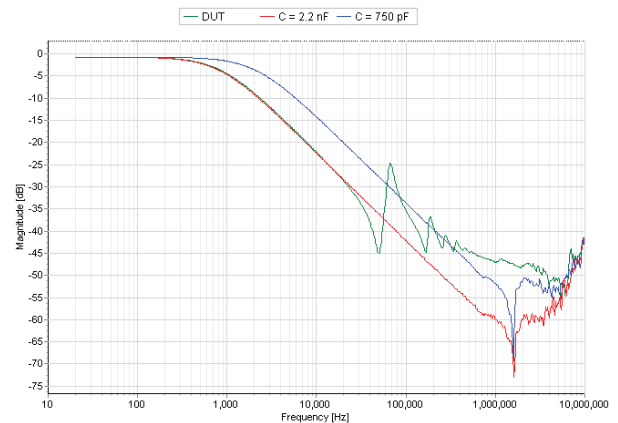


Figure 11: Impedance frequency characteristics of the Brown Boveri distribution transformer.

The impedance frequency characteristics of the Breda transformer are shown in Figure 12. For this test object the first resonance occurs at 300 kHz and according to the corresponding test curve in Figure 12 the capacitance has decreased to 1.5 nF compared to the low-frequency reference value of 3.7 nF determined by the MIDAS measurement. At 600 kHz the next resonance occurs and the capacitance drops to 750 pF. At approximately 1 MHz the capacitance is further reduced to only 200 pF. All capacitance values have been extracted from the corresponding database curves (cf. Figure 12) which is the core principle of this measuring technique.

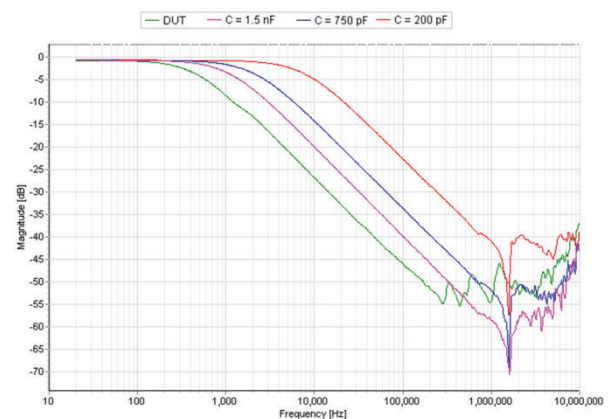


Figure 12: Impedance frequency characteristics of the Breda distribution transformer.

4.2 Rotating machines

A stator winding of a motor (cf. Figure 13) with nominal voltage $U_n = 5.5$ kV (according to the name plate of the stator) has been tested.



Figure 13: Stator winding with $U_n = 5.5$ kV.

The equivalent capacitance of the stator winding (all phases together to ground) measured by the MIDAS instrument is $C = 220$ nF which perfectly correlates with the low-frequency capacitance estimated from the impedance frequency characteristic shown in Figure 14. After several resonances, the capacitance drops to only 2.2 nF in the frequency range from 400 kHz to 1 MHz which is one hundred times lower than the equivalent capacitance at 50 Hz. The most distinct feature to be noticed from Figure 14 is the nearly constant impedance from 20 kHz to 800 kHz which is typical of transmission lines or cables.

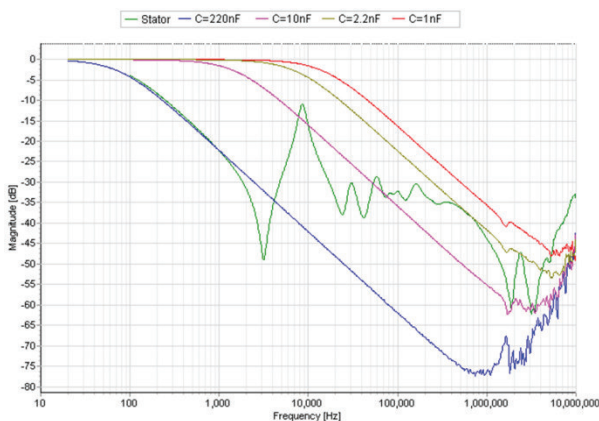


Figure 14: Impedance frequency characteristics of the stator of a rotating machine.

The impedance in the mentioned frequency range still varies but as seen in Figure 18, the remaining variation has virtually no impact on the PD pulse spectrum. I.e. for PD measurement in the 100 – 500 kHz range, the calibration pulse spectrum remains constant indicating valid measurement.

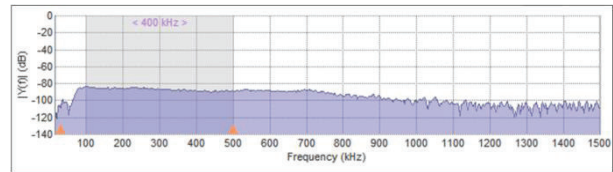


Figure 15: Frequency spectrum of a PD calibration pulse applied to the stator winding of Figure 13.

5 CONCLUSION

A newly developed measuring technique has been implemented to verify and confirm that the capacitance of HV devices with winding elements decreases with frequency. This is caused by local resonances due to the complexity of the design and the RLC character of these devices.

Using the modified FRA measuring technique presented in this paper allows finding resonance frequencies, estimating the approximate DUT capacitance for a specific frequency range and deriving proper coupling capacitor values for PD measurement. Simple on-site measurements can be conducted, since FRA is supplied with large and easy-to-use connection clamps, and the measurement is performed under safe conditions for both the test equipment and the operator.

Depending on the frequency range some parts of the complex RLC network representing the DUT are excluded when extracting the equivalent capacitance. On the other hand, it is difficult to predict the propagation path of the PD current pulse through the complex RLC network of the DUT since by mutual capacitive coupling the PD pulse can cross-couple through the entire system. Hence, even pulses originating deep inside the winding can be measured and recorded.



REFERENCES

- [1] H. J. Weber, "Partial Discharge Measuring Techniques". Tettex-Information 21, 1984
- [2] G. Stone, "Importance of bandwidth in PD measurement in operating motors and generators", IEEE Transactions on Dielectrics and Electrical Insulation, vol. 7, no. 1, pp. 6-11, Feb 2000
- [3] E. Bogatin, "Signal and Power Integrity – Simplified", 2nd Ed., Chapter 6, Prentice Hall, 2010
- [4] IEC TS 60034-27, "Rotating electrical machines - Part 27: Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines", 1st Ed., 2006
- [5] Haefely Test AG, "FRA 5310 - Sweep Frequency Response Analyser for Power Transformer Diagnosis", Product brochure, Switzerland, p. 3, 2014
- [6] Haefely Test AG, "MIDAS 288x Mobile Insulation Diagnosis & Analyzing System", Operating Instructions, V.1.9, Switzerland, p. 168, 2012

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