Innovative application of frequency response analysis for partial discharge measurement

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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 $1/10^n$ 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 μF 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 $f > f_{res}(C_3)$. 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].

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

\[
Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{5 \times 10^{-6}}{3 \times 10^{-9}}} \approx 30 \Omega
\]

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.

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:

\[
A = 20 \cdot \log \left( \frac{I_f}{I_0} \right) \quad [A] = \text{dB}
\]

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.](image)

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

$$C_{DUT} \approx \frac{1}{2\pi f R_g A}$$

(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 $R_g$.](image)

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).](image)

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 L3 and C4 (L2 and C2). Beyond this first resonance the response of VF3 is purely inductive while for VF1 a second resonance arises at 411 kHz due to L3 and C3. Above this second resonance the frequency response of VF1 is dominated by the capacitive behavior of C3 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).

![Figure 6: Frequency response of the given RLC circuits.](image)

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 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: $R_g = 1 \, \text{kΩ}, 10 \, \text{kΩ}, 100 \, \text{kΩ}, 1 \, \text{MΩ}$.

$‡$ 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 $HV = 10.5 \, \text{kV}$, $LV = 400 \, \text{V}$ 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 ($HV = 15.5 – 16.5 \, \text{kV}, LV = 400 \, \text{V}, S = 75 \, \text{kVA}$) 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 δ (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.

The 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.

Again, the reference capacitance at 50 Hz has been measured using a Tettex MIDAS 288x resulting in $C = 2 \text{ nF}$ and $C = 3.7 \text{ nF}$ 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 $C = 750 \text{ pF}$ curve.

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.
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.

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

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