Reproducible on-site measurements of transfer function on power transformers in frequency domain

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Abstract

By the analysis of transfer function mechanical deformations or displacements of transformer windings can be detected. This article discusses the effect of variations in the configuration of the measurement circuit, a topic that is handled within CIGRE WG A2.26. Of further concern is the selection of a meaningful upper frequency limit, from where beyond measurements of transfer functions are not practicable on site. A set-up concept for high reproducible measurements that has been developed by the authors shows satisfying results.

1. Introduction

The evaluation of the transfer function is a sensitive diagnostic method to detect mechanical variation of the active part of a power transformer. Deformations caused by short circuit currents or transportation forces result in variation of the transfer function. For acquisition of the transfer function with the off-line sweep frequency method presented in this paper a frequency variable low-level sinusoid signal with known voltage $\underline{U}_1$ is applied at one terminal of an off-line power transformer and picked up again at another terminal and voltage $\underline{U}_2$ the transfer function

$$\underline{H}(f) = \frac{\underline{U}_2(f)}{\underline{U}_1(f)} \qquad (1)$$

is calculated [3]. Fig. 1 shows measurement principle on the HV star winding between phase U and neutral point of a distribution transformer.

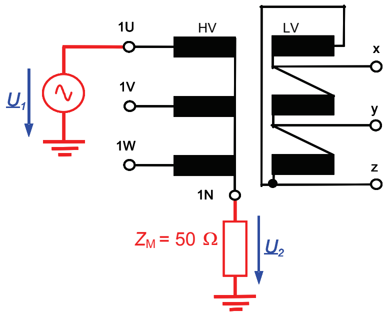

Fig. 1: SFRA measurement at 1U and 1N

A question of interest is the maximum frequency up to which the measurement is evaluated. Under laboratory conditions, measurements up to 10 MHz have been carried out in [1]. However at on-site measurements the frequency range is usually limited to lower frequency boundaries. Type- or phase-based comparison methods are limited to noticeable lower frequencies than 10 MHz [2].

2. On-site measurements

2.1. Reproduction of measurements

For reliable detection of actual mechanical variations with the FRA method it must be assured that the transfer function is not influenced by inaccuracies of the measurement set-up. The measurement circuit itself and the grounding system has a certain physical dimension and can have an impact on the acquired transfer function, especially in the high frequency range starting at a few 100 kHz.

Fig. 2 shows repeated measurements up to 5 MHz of the transfer function (high voltage winding) on the same transformer (110/10 kV, 40 MVA, single phase) with identical configuration. The transformer has been in service in the meantime. The curves show only slight deviation in the high frequency range, proving the measurement set-up to give excellent reproducibility.

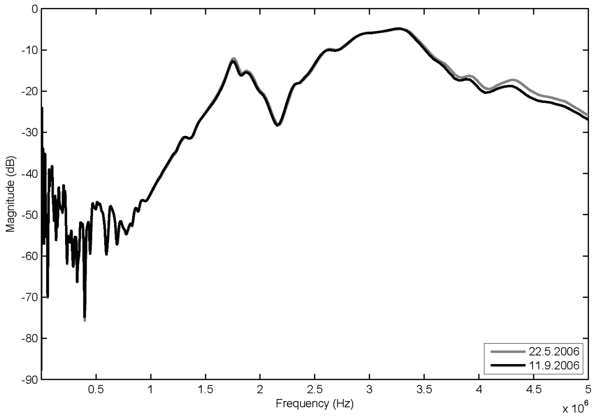

Fig. 2: Repeated measurement, 110/10 kV 40 MVA single phase transformer

The tap changer position, all used connection and grounding points at the transformer have to be clearly recorded. Also type and length of grounding connectors should be remarked in the report.

2.2. Measurement voltage

The transformer's magnetic core shows variant behaviour not only after magnetization [4] but also on variation of measurement voltage, as shown on a 20/0.4 kV 800 kVA distribution transformer in Fig. 3. There was no influence of measurement voltage at higher frequencies. When a measurement is repeated on the same test specimen, it must be ensured that the same measurement voltage is used. Otherwise there will be deviations in the low frequency range that might be accidentally detected as fault.

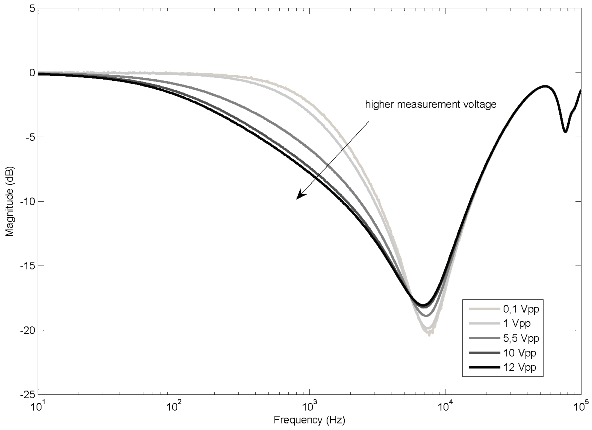

Fig. 3: Influence of measurement voltage on transfer function

2.3. Ground connections

A crucial quality factor is accurate handling of ground connectors between the earthed transformer tank and the shielded wires of the measurement device. The authors experienced good results with thin wired aluminium braid conductors to reduce skin effect and inductivity.

Common connection points for earth conductors at the tank are bushing bolts that are usually covered with anticorrosive paint and therefore can be a source of low-grade contact if the coating is not removed accurately. Fig. 4 shows a clamping method to provide laminar contact between earth braid and transformer tank.

Fig. 4: Clamping aluminium braid for ground contact

Three measurements have been carried out on a 40 MVA single phase transformer at the 110 kV terminals with identical set-up. The only variation was the connection between transformer tank and the ground connector of the receiver arm as described in Table 1. The connector lead that applied the voltage at another terminal of the power transformer was connected with it's shielding to the transformer tank by standard aluminium braid connection all time. The measurement impedance Z_M was 50 Ohms.

Table 1: Variation of grounding

Measurement	Description
"no grounding"	no connection with transformer tank at receiver side
"poor grounding"	remaining paint and oxides on screw, connection with clamp
"good grounding"	paint and oxides accurately removed, connection with clamp

The measurements show significant deviation already at moderate frequencies (Fig. 5). This can be a tremendous source for misinterpretation of measurements.

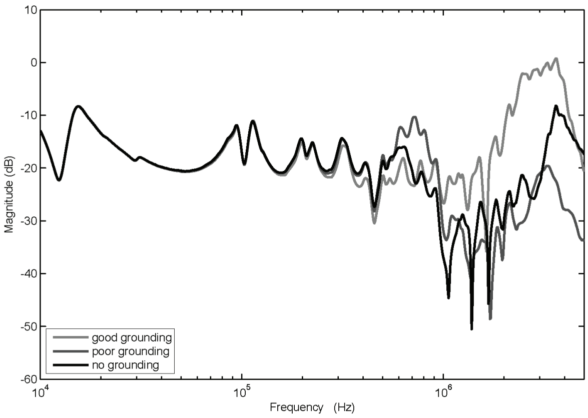

Fig. 5: Deviation caused by quality of earth contact at receiver side, 40 MVA transformer

2.4. Measurement impedance

Using high impedance Z_M (often 1 MΩ) for measurement of voltage $\underline{U}_2$ will result in bad matching of standard 50 Ohms coaxial cable connecting transformer and measurement device and unsatisfying high frequency behaviour:

For on-site measurements on large power transformers a typical lead's length is $l = 15$ m. As estimation, a electrical line can be considered as short if

$$l < \frac{\lambda}{10} \tag{2}$$

For FRA application, this limit would be reached at the frequency

$$f_{Short} = \frac{c}{\lambda_{Short}} = \frac{c}{10 \cdot l} \approx 1.33\ \text{MHz} \tag{3}$$

where c is the propagation speed of standard coaxial cable with a relative permittivity $\varepsilon_r = 2.25$:

$$c = \frac{c_0}{\sqrt{\varepsilon_r}} \tag{4}$$

If the cable is not terminated with its impedance, above this frequency standing waves will result from reflections and the measured voltage $\underline{U}_2$ will heavily depend on the length of the cable.

This problem can be overcome if the measurement termination impedance is decoupled from the coaxial cable and placed in direct proximity to the transformer's connection point, virtually reducing cable length to zero. Also winding end-to-end measurements with high measuring impedance can result in transfer functions without distinct resonance peaks in the low frequency domain as there is only weak excitation of the magnetic core, as shown in Fig. 6. Low impedance may result in low signal-to-noise ratio, depending on the test specimen.

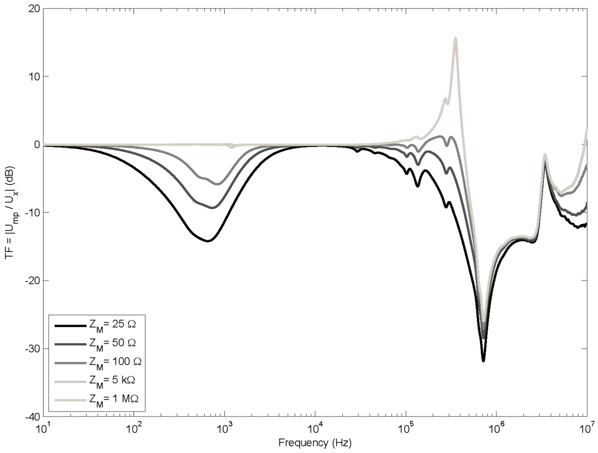

Fig. 6: Transfer function of LV winding, variation of measurement impedance

Two main sources of disturbances have been identified:

- Inductive currents at rated power frequency caused by nearby high current-carrying conductors
- Capacitive coupling of noise voltage caused by corona discharge at high voltage lines or equipment

Fig. 7 shows on-site measurements of inter-winding transfer function on a 1100 MVA 400/27 kV generator transformer with different measuring impedances in noisy environment. The transformer was in proximity to an energized high voltage line with corona discharge (distance about 20 metres). Whilst inductive interferences only manifest at rated power frequency in the transfer frequency plot, noise that is caused by corona discharge can be detected over a wide frequency range. The higher the measuring impedance, the more distinctive is the interference making high impedance measurement (e.g. 1 MΩ) difficult. For most measurements an impedance of $Z_M = 50\ \Omega$ is a trade-off of noise immunity and dynamics.

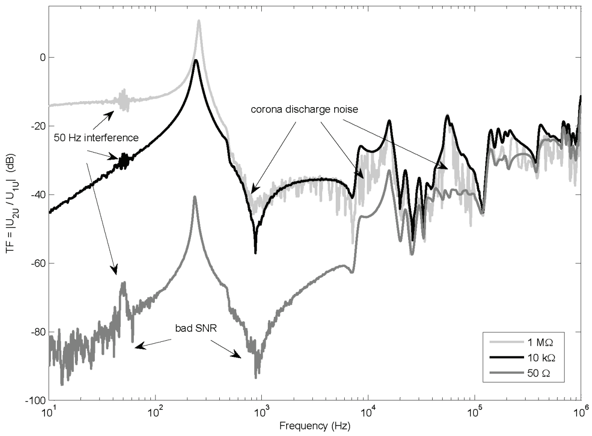

Fig. 7: Influence of interferences on different measurement impedances

3. Failure of a 33 MVA single phase generator transformer

To obtain winding fingerprints, FRA measurements have been performed on a 110/6 kV 33 MVA single phase 16.7 Hz transformer in May 2006. FRA plots were recorded for the transfer function of the HV winding (terminals U and V) and the LV winding (terminals u and v). The transformer was constructed as single winding without neutral point terminal (see Fig. 8). The measurement impedance Z_M was 50 Ohms.

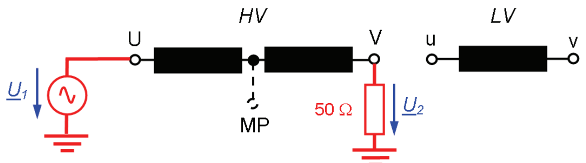

Fig. 8: 33 MVA 110/10 kV single phase transformer

The failure occurred in September 2006 after lightning hit an overhead high voltage line. After this event the FRA measurements were repeated. As shown in Fig. 9 and Fig. 10, the FRA plots before and after the damage are totally different. This encouraged the decision not to consider repair of the transformer.

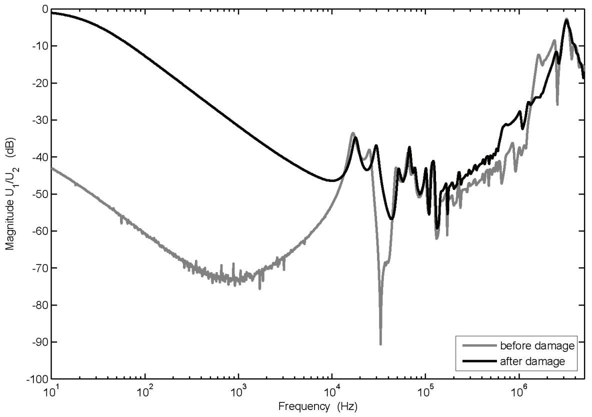

Fig. 9: FRA plot of HV winding, no damage was found on winding

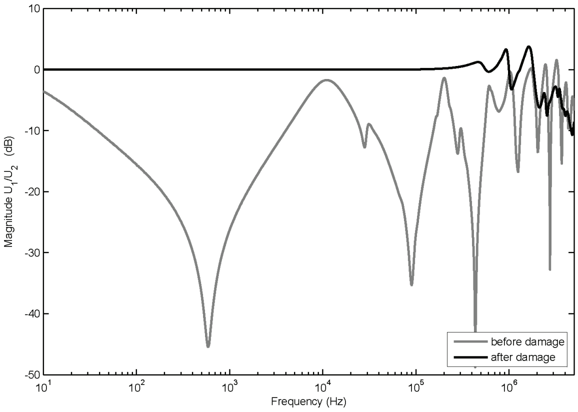

Fig. 10: FRA plot of LV winding with radial buckling

The transformer was scraped in January 2007 when the tank was opened and the active part was available for visual inspection (Fig. 11 and Fig. 12).

Fig. 11: Undamaged HV winding

As expected, the low voltage winding was severely damaged with huge radial buckling. It is remarkable that no damage was found at the high voltage winding itself, although the FRA plot showed strong deviation in the full frequency spectrum (Fig. 9 and Fig. 11). These results show that the transfer function of a winding is not only influenced by the winding itself but from the complete mechanical construction of the active part.

4. Conclusions

Depending on local situation, high impedance on-site measurements of transfer function at large power transformers can be difficult due to interference. When extending the frequency range for SFRA measurements the test leads cannot be regarded as electrically short and proper termination is necessary.

As the measurement set-up has a certain dimension and high frequency deviations are easily caused by grounding issues, practical on-site measurements of transfer function should be reasonable limited to an absolute maximum of 5 MHz. If set-up quality and accuracy is poor a much lower maximum usable frequency will be achieved.

Fig. 12: Radial buckling of LV winding

5. References

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