

# Circuit design for reproducible on-site measurements of transfer function on large power transformers using the SFRA method

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**Abstract:** By the analysis of transfer function mechanical deformations or displacements of transformer windings can be detected. For on site measurements on large power transformers essential attention has to be put on accurate cabling and handling of grounding conductors. Of further concern is the selection of a meaningful upper frequency limit, from where beyond measurements of frequency responses are not practicable on site. A set-up concept for reproducible measurements that has been developed by the authors shows satisfying results. Investigations on the transfer function of power transformers identical in construction have been carried out: Depending on the type, size and winding construction the transfer function of a winding system of identical transformers is well comparable to frequencies above 1 MHz. A mathematical approach to evaluate the quality of different comparison methods using the coherence function is presented.

## 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 result in variation of the transfer function.

Some authors of technical publications (e.g. [1]) propose to extend the frequency range in which the transfer function is evaluated to at least 10 MHz and prove deviations in the transfer function from 1 MHz up to high frequency ranges by artificial mechanical deformation of a transformer winding.

## 2 THE SFRA METHOD

To acquire the TF (transfer function) with the SFRA method (Sweep Frequency Response Analysis) presented in this paper, a frequency variable sinusoid signal with known voltage is applied on one terminal of an off-line power transformer. On a second terminal the signal of the same frequency is picked up by a sensor. With this procedure the transfer function

$$\underline{H}(f) = \frac{U_2(f)}{U_1(f)} \quad (1)$$

between two terminals of a power transformer can be acquired in frequency domain with magnitude and

phase. Through variation of signal frequency the transfer function can be evaluated in the desired frequency range [2]. Fig. 1 shows the equivalent circuit of a measurement between 1U and 1N on a typical delta-wye distribution transformer. Fig. 2 shows the practical realisation of the circuit on a test specimen with complex, frequency variable impedances. The main difference between ideal and real circuitry is the distributed grounding system and non-zero length of the measuring leads.

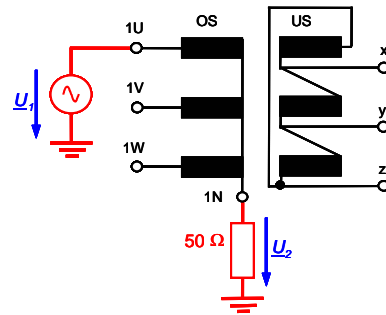


Fig. 1: SFRA measurement principle

### 2.1. On site acquisition of transfer function

As the measurement principle is based on the comparison of frequency plots, the greatest challenge for on site acquisitions is a good reproducibility of measurements that are repeated after a certain time. The measurement circuit itself and the grounding system has a certain physical dimension and has an impact on the acquired transfer function, especially in the high frequency range starting at a few 100 kHz. Another fundamental requirement is that the measurement instrumentation for transfer function must be independent from local grounding conditions, e.g. for power transformer transport.

To ensure repeatability of FRA measurements also after long time with a measuring set-up as identical as possible, focus has to be put on accurate documentation. The tap changer position, all used connection and grounding points at the transformer have to be clearly recorded. Taking detail photographs has proven to be very helpful. The type and length of grounding connectors have to be remarked in the report.

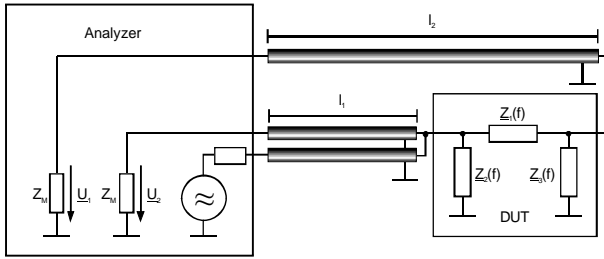


Fig. 2: Realisation of measurement circuitry

All measurements presented in this paper have been performed with the Tettex FRA 5310 measurement system manufactured by Haefely Test AG.

## 2.2. Handling of Terminals

Particularly on transformers with high nominal voltages and large power rating cabling work takes significant time and because of the large dimensions it determines the overall measurement duration. In principle it is possible to ground or short circuit unused winding systems, although perfect grounding or short circuit of windings is impossible to realise especially at higher frequencies. If the measurement is repeated, identical cabling set-up must be used. On reproduction measurements with several cabling steps small deviations in the set-up will accumulate and possibly affect deviations of the transfer function.

Under the aspect of good reproducibility the authors did not ground or short circuit unused terminals at their measurements and tried to keep number and length of used measuring wires as small as possible. Fig. 3 shows the typical connection of the measurement clamps and ground connectors to the transformer's neutral point equipped with a 400 kV bushing.



Fig. 3: Measurement connection on bushing stem and ground connection with aluminium braid on a 400 kV bushing

If deviations occur on chronological measurements on a transformer there are aspects beside an actual deformation of windings that can be held responsible for changes in the transfer function:

- variations caused by the measurement set-up

- variations of transfer characteristics of other parts in the signal path, like bushings or tap changer contacts

As transformer high voltage bushings are connected to the terminal lead by a flexible conductor, the position of the conductor may vary between transformers identical in construction or after maintenance. This might be source of high frequency deviations. The effect of variations on tap changer and bushings on the transfer function has not been investigated yet but cannot be ruled out in principal.

## 2.3. Influence of Measurement Voltage

The transformer's magnetic core shows variant behaviour not only after magnetization [6] but also on variation of measurement voltage, as shown in Fig. 4 on a 20/0.4 kV 800 kVA distribution transformer. There was no influence of measurement voltage in 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.

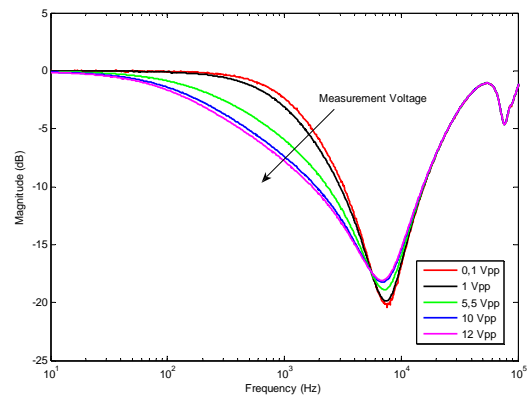


Fig. 4: Influence of measurement voltage on transfer function

## 2.4. Influence of Bushings

Capacitive controlled bushings with their stacked conducting layers basically show high pass behaviour between the bushing stem and the root point connected to the transformer tank. To investigate the influence of a capacitor bushing the transfer function between the low voltage terminals 2U and 2N was determined. Afterwards the measurement was repeated with identical parameters but a 123 kV bushing was put in series between the terminal and the receiver. The bushing root point was connected with a very short piece of aluminium braid to the transformer's tank; the bushing's test tap was grounded. Fig. 5 proves an influence of the capacitor bushing on the transfer function even below 1 MHz.

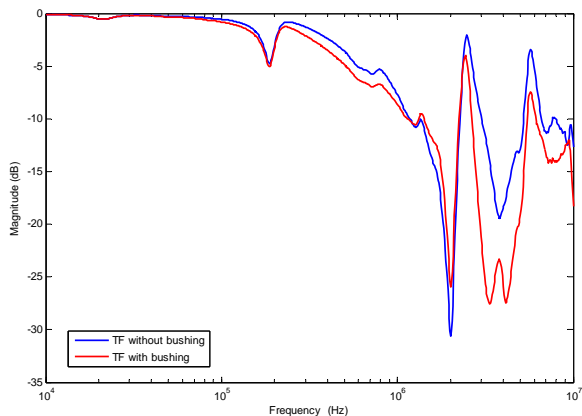


Fig. 5: Influence of bushing on transfer function

## 2.5. Measurement impedance

Using high impedance  $Z_M$  (e.g. 1 M $\Omega$ ) will result in bad matching of the 50 Ohms coaxial cable connecting transformer and measurement device and unsatisfying high frequency behaviour. This problem can be overcome if the measurement termination impedance is placed in direct proximity to the transformer's connection point, reducing cable length  $l_2$  to zero. Also winding end-to-end measurements with high measuring impedance can result in transfer functions without distinct resonance peaks if the winding impedance is rather low [7].

## 2.6. Ground connections

The earthed transformer tank has to be connected to the grounding system of the measurement device. It has become evident that the connection between tank and measurement connector has considerable influence on the transfer function. To provide good reproducibility of FRA measurements, the specification of a grounding strategy must be an integral part of the acquisition procedure. Furthermore the set-up must be realisable also on largest power transformers.

In the context of comprehensive analysis it has been realised that broad, thin-leaded aluminium braid for connection of measurement ground with the transformer tank is an acceptable compromise within cost and benefit. The fundamental difference of braid conductor and conventional wire is not only a reduced inductivity but also the noticeable reduction of the frequency-dependant skin effect. The current displacement is remarkable already at measurement frequencies of 50 kHz.

Another vulnerability of transfer function measurements is the contact point of grounding conductor and transformer tank. As the tank is usually coated corrosion protection paint, the coating has to be removed for satisfying contact. For good high frequency behaviour the contact should not be punctual but laminar.

Poor grounding can cause significant deviations even below 1 MHz and can therefore be tremendous source for mismeasurements that are hard to detect. Fig. 6 shows measurements on a 40 MVA 110/10 kV single phase transformer with different contact quality on the receiver arm of the measurement device.

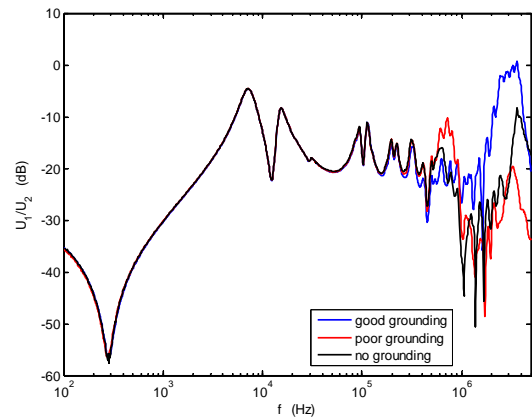


Fig. 6: Transfer function of one 40 MVA transformer, different grounding contact quality of receiver arm on bushing root point

To investigate the influence of an altered ground set-up on the acquired transfer function the measurement device was connected to the transformer tank with an additional ground connector (copper wire, length 1m) during measurements on a single-phase 110/132 kV 50 MVA coupling transformer. Here the transfer functions showed up identical characteristics up to about 1.6 MHz, at higher frequencies there was significant deviation in the magnitude of the transfer function but also in the position of resonance peaks, see Fig. 7.

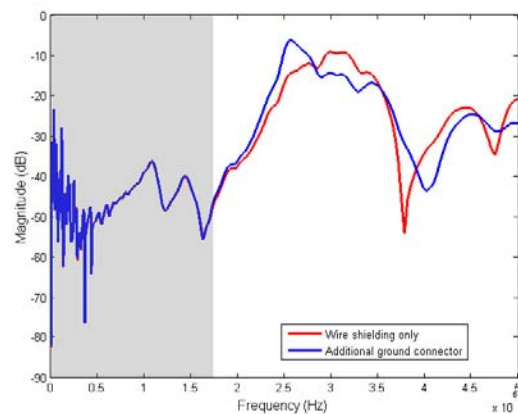


Fig. 7: Deviations of TF caused by alteration of ground connectors between transformer and measurement device

### 3 METHODS OF COMPARISON

#### 3.1. Time-based comparison

The most common method is the time-based comparison of transfer functions, also called “finger print measurement”. These can be for example measurements on annual inspections or before and after transports of power transformers. With a careful and accurate set-up and a high frequency capable grounding concept one will get satisfying results up to several MHz. Fig. 8 shows the repetition of a measurement on a 110/10 kV 40 MVA single phase transformer after five months with almost no deviation. This proves that the chosen measurement set-up provides excellent reproducibility. The transformer was in service before and after the measurements.

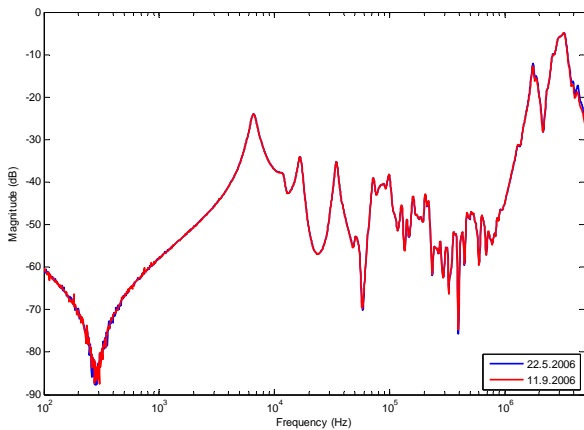


Fig. 8: Reproduction of TF after time, HV winding, 40 MVA single phase transformer

#### 3.2. Phase-to-phase comparison

Depending on the size and type of construction a phase-to-phase comparison is possible up to a maximum frequency ranging widely from about 40 to 700 kHz. The transfer functions of the low voltage windings of a 400/15 kV 273 MVA power transformer in Fig. 9 show good similarity up to about 350 kHz. In the frequency range below 1 kHz there is also the typical deviation of the middle transformer winding (“V-Mp”) that is caused by the geometry of the magnetic core. The asymmetry of the core, different stray capacitances and varying length and position of terminal leads of the windings limit the usable frequency range.

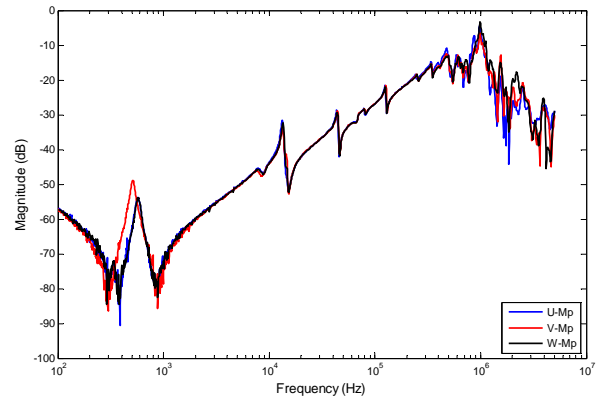


Fig. 9: Phase-to-phase comparison, HV star winding, 273 MVA generator transformer

#### 3.3. Sister unit comparison

In large power plants or substations often power transformers can be found that are apparently identical in construction. If the transformers have sequential serial numbers it can be assumed with high likelihood that the mechanical construction is identical. Please note that even in a series of transformers with identical characteristics modifications in the mechanical and electrical design are possible [5].

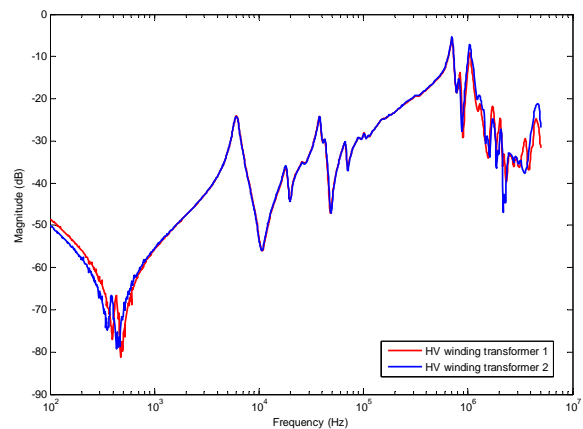


Fig. 10: Sister unit comparison, HV star winding, 1100 MVA generator transformers

Fig. 10 shows the transfer functions of two 400/27 kV 1100 MVA transformers that are connected in parallel to a large generator and to one high voltage feeder. These transformers have been in service since 1978. Fig. 11 shows the low voltage windings’ transfer functions of two 400/15 kV 273 MVA sister transformers connected to separate generators in a hydro power plant.

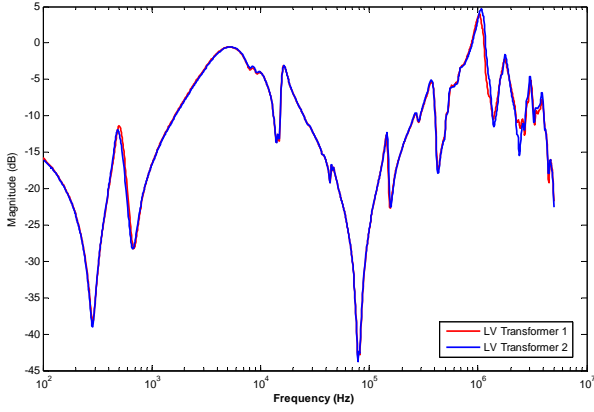


Fig. 11: Sister unit comparison, LV wye winding, 273 MVA generator transformers

### 3.4. Mathematical approach

There are different ways to investigate the likeness of two transfer functions, e.g. calculation of the difference function or the coherence function [3], [4]. The coherence function gives information on the analogy of two functions at a frequency  $f$  and is defined as:

$$\gamma^2_{XY}(f) = \frac{|G_{XY}(f)|^2}{G_{XX}(f) \cdot G_{YY}(f)} \quad (2)$$

This function provides values between 0 (no correlation) and 1 (full correlation of both signals). Already small deviations in magnitude and phase result in variation of the coherence function from  $\gamma^2_{XY}(f) = 1$ . However the coherence function gives only information about one specific frequency  $f$ .

If the coherence function is scaled from 0 for full correlation and is summed up, a monotonic rising function is obtained, that gives information about the total deviation  $\delta$  of the transfer functions up to a frequency  $f_1$ :

$$\delta(f_1) = \sum_{k=f_0}^{f_1} 1 - \gamma^2_{XY}(k) \quad (3)$$

Fig. 12 shows the coherence and error function for two transfer functions with significant deviation.

Under the assumption that there is no mechanical defect when comparing the transfer functions, an arbitrary level  $\delta_{Limit}$  is defined and the corresponding frequency  $f_{Limit}$  is calculated up to which two transfer functions can be regarded as similar. The value of  $f_{Limit}$  characterizes the frequency at which the two compared transfer functions diverge more than the tolerated measure  $\delta_{Limit}$ . This method may only be used if transfer functions with identical frequency sampling points are provided.

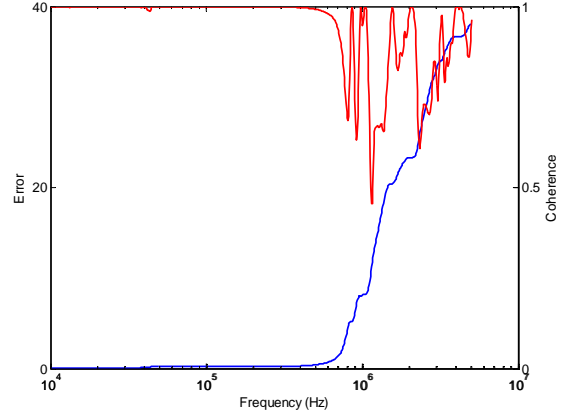


Fig. 12: Coherence and sum error

To determine the upper frequency limit in this investigation the evaluated lowest frequency was defined to be 7 kHz to mask time variant influence of the magnetic core [6]. The error level was chosen to  $\delta_{Limit} = 1.5$ . As shown in Fig. 13, three different sizes of generator transformers were investigated.

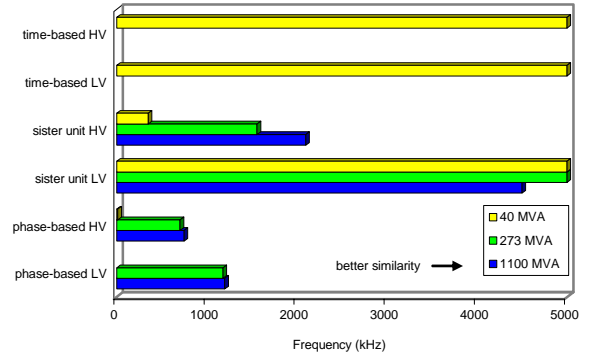


Fig. 13: Quality of comparison,  $\delta_{Limit} = 1.5$

The investigations prove that the transfer functions of the same phases of transformers identical in construction are much more similar than the different phases of one transformer compared to each other. Obviously, constructive tolerances have less influence on the transfer function than the different length and position of terminal leads and the general asymmetry of the winding arrangement in the transformer tank. The phase-based comparison is limited to a much smaller frequency range. Compared to the 40 MVA transformer, the large 273 MVA and 1100 MVA transformers are comparable in a larger frequency range, especially for the high voltage windings.

Constructive tolerances cause slight deviation in the transfer function in the region of 1 MHz and above. From the experience of the authors, at most power transformers transfer functions of low voltage windings identical in construction are similar up to higher

frequencies than transfer functions of high voltage windings. This is due to the more complex construction of the winding, longer terminal leads (e.g. tap changer) and larger bushings, but the individual influence has not been investigated yet.

Please note that the authors do not recommend the coherence function as solely tool for interpretation on transfer functions. Deviations in magnitude that are sometimes caused by poor set-up will also be detected by the coherence function and may lead to misinterpretation.

## 4 CONCLUSIONS

Reproducible on site FRA measurements above 1 MHz are possible, but full attention has to be put on the quality of the measurement set-up. Grounding strategies with low inductance and little skin effect are essential for congruent measurements.

FRA measurements on power transformer sister units show up a much better correlation than a comparison of different phases of one power transformer. The experience shows that usually identity of transfer functions of low voltage windings can be obtained to higher frequencies than on high voltage windings. Constructive tolerances manifest in slight deviation of the transfer function above 1 MHz.

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.

## 5 ACKNOWLEDGMENTS

The authors would like to acknowledge the kind support from Deutsche Forschungsgemeinschaft (DFG) and from various power utilities for making measurements possible.

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