

## Technique and evaluation of FRA-measurements on large power transformers

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**Abstract:** Although the frequency response analysis method (FRA) or transfer function method, respectively, is already a common and efficient method allowing the detection of geometric changes in the active part of transformers and in reactors, research on the optimum application and on the limits of significance and unambiguousness is still going on. This contribution describes in detail the measurement of the frequency depended complex voltage-voltage (v-v) transfer function. Regarding the manifold possible impedance- transmittance- and v-v-transfer paths the authors found the most meaningful results, if always one end of a winding is put on earth and the input and output connections are loaded with an impedance of 50  $\Omega$ . It is finally shown, that a complex locus plot is an effective and meaningful instrument to compare transfer functions and to check small changes.

### 1. Introduction

Since power transformers are key components at all levels of the power grid, failures and outages of any reason cause considerable and unforeseeable costs as well as power outages. The international survey of CIGRE [1] shows typical failure rates for large power transformers for operating voltages up to 300 kV in the range of 1% to 2% p.a.. Although this is a moderate number, the damage of a single large transformer causes considerable economic disadvantage. Repair costs are expected to rise in future because of the shutdown and merging of companies and the growing transport distances. This development increases the importance of transformer condition assessment by means of a variety of diagnosis methods aiming at a better planning of maintenance.

The most significant diagnostic methods focus directly on the insulation part of transformers since finally most of the failures lead to an internal dielectric breakdown of the transformer. Primarily, oil examinations, measurement of partial discharges (PD) and measurement of the dielectric response or relaxation currents, i.e. polarisation and depolarisation currents (PDC) or dissipation factors at low frequency are the most meaningful methods in this field [2, 3].

A further important information about the condition of the active part of the transformer can be achieved by the investigation of small changes in the high frequency behaviour of the windings.

Frequency spectra of measured transfer functions (range: 20 Hz to 2 MHz) are in general sensitive to deformations or displacements of the winding assemblies, caused by dynamic forces in service or from

excessive mechanical acceleration during transports or by magnetic forces evoked by external short circuit currents [4, 5].

Although a displacement of a winding as it particularly happens with old and brittle paper insulation does not necessarily lead to an immediate transformer failure, it may increase the risk of insulation breakdown on the occasion of the next over-voltage or short circuit stress.

The crucial advantage of the FRA- or TF -method is obviously given through bypassing the costly inspection of the opened transformer.

Original investigations with transfer functions used time domain based methods, where an impulse or step voltage was applied at an input winding. Both, the input signal and the response signal at the output winding were digitally recorded. These signals were analysed by Fourier transform and the output spectrum was divided by the input spectrum [4 ... 10]. Within the last fifteen years the frequency domain method became more common, since it exhibits excellent signal to noise ratios and, therefore, a convincing sensitivity to small signal differences. Recent investigations on power transformers monitoring with the FRA-Method use signals generated during service and thus time domain methods have again been improved a lot [7].

Nowadays, several user-friendly measuring systems are available consisting of a swept frequency generator and a real or complex ratio measuring device, including the software for evaluation, database storage and comparison. But also general purpose network analysers offer all necessary features for practical measurements even on-site.

Since FRA can be performed with a relatively small time expenditure, it is not only profitable for very large grid interconnecting transformers, but it is advantageously applied also at substation transformers and even smaller units.

Since the beginning of the widespread use of FRA many sensitivity studies with and without application of statistical tools were already performed [7, 8, 9, 10].

In this context, possible disturbing influences on the result, which can pretend a geometric change are examined too (for instant a differing temperature [7])

The following description demonstrates the experiences gained mainly with large transformers in Switzerland and adjacent countries. During an extended research project the method was investigated and optimised in practical use.

## 2. Technique of measurement

This work exclusively treats the FRA method in the frequency domain. In the literature this version is often designated as “swept” FRA (SFRA).

Time domain impulse measurements in combination of Fourier transform have not been followed up for the following reasons.

At low frequency the signal transfer between input and output windings is determined by inductive and at high frequencies by capacitive coupling. The middle range of some kHz to some 10 kHz shows geometry-dependent resonances where very high attenuation may occur (see examples of transfer functions in figure 4).

Especially at the high frequency end (range 500 kHz to some MHz) the capacitive coupling is usually strongly predominating. However the range above 1 MHz depends only on the geometry of the measuring connections and the bushings. Therefore this range cannot provide reliable information about the winding geometry. Thus the predominant signal levels at high frequencies mask the interesting contributions at lower frequencies. Either the used transient recorder must have a very high dynamic range or the measured output signal must be averaged or possibly treated with a low pass filter. These problems affect the signal and question the reproducibility of the FRA method in the time domain combined with FFT. This reflection lead the decision to measuring in the frequency domain.

The principle of FRA-method in frequency domain and the necessary equipment is shown schematically in Figure 1. The authors use a Hewlett Packard model HP 8751 network analyzer SFRA of transformer windings.

Figure 2 shows different possibilities for the measurement connections.

Normally all displayed combinations are investigated especially when a transformer is measured for the first time to establish an initial reference data set.

Input and output of the network analyzer are connected via screened coaxial cables to the terminals of the windings under test. In order to reach a reproducible high frequency part of the spectrum, it is very important to connect the cable shields in the shortest way to the ground potential of the transformer tank (figure 2d).

The output of the network analyzer produces a swept sinusoidal signal, which is conducted to the input winding terminal. To compensate for the influence of the input lead, the signal at the input terminal must be sensed and measured with a reference input (R) of the analyzer. Finally the transferred signal at the output terminal at another winding or at other turns of the same winding is conducted to the measuring input (A) of the analyzer.

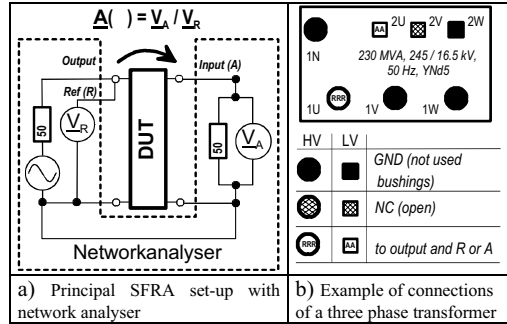


Figure 1: Set-up for frequency response analysis (FRA) in frequency domain.

Our experience is, that transfer admittance measurements (voltage to current transfer functions) are normally less sensitive to small geometrical changes than voltage to voltage transfer measurements are. The reason for this is that the necessary HF-current transformers render only a small output signal. Therefore, the authors use only the voltage to voltage transfer measurements corresponding to figure 2. In this figure three main cases are distinguished corresponding to their low frequency (LF) coupling principle:

- “M-set-up” LF coupling by the mutual inductance.
- “C-set-up” LF coupling by interwinding capacitance.
- “L-set-up” LF coupling by the stray inductance of a winding (other winding short circuited).

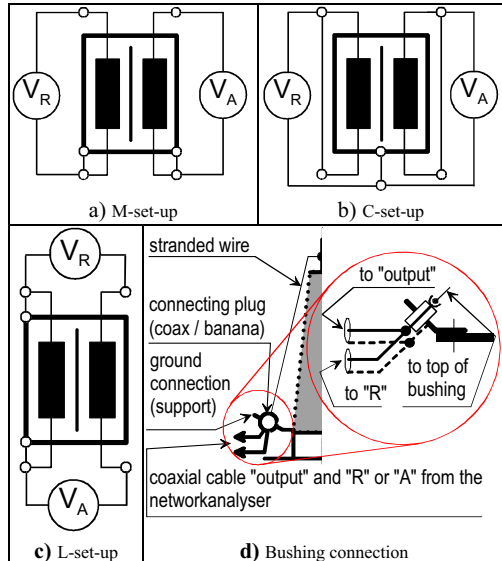
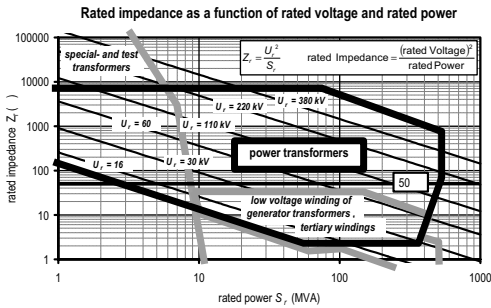


Figure 2: Connection of transformer terminals for different measuring set-ups (a, b, c) and details of bushing connection (d).

The input and output impedances of a common network analyzer affect the frequency spectrum and are therefore consequently kept at 50 Ω. This is admissible since the FRA method is normally used as a pure comparative method. Advantageously, the measuring impedance of 50 Ω avoids the influence of the coaxial cable length on the transfer function.

As it is shown in figure 3, the measuring impedance of 50 Ω is situated in the range of the characteristic impedance of power transformers at power frequency. This fact guarantees a sufficient signal power also during the FRA measuring.

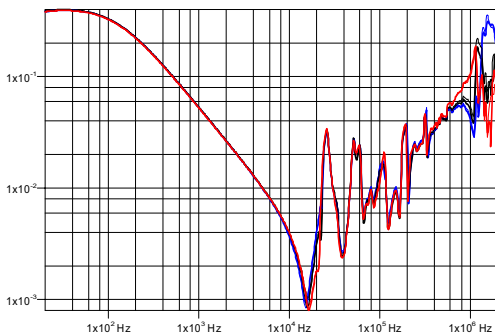


**Figure 3:** Natural transformer impedance given by the nominal voltage and power and comparison to the 50 Ω measuring impedance for FRA.

Reference data for the required FRA spectra comparisons are provided by:

1. Earlier measurements, e.g. at the factory.
2. Measurement of transformers of the same design [7].
3. Comparison between the three phases or poles of the same unit.

Figure 4 shows an example of superposed FRA-spectra on the three phases of a 160 MVA power transformer without any indication of a winding displacement.



**Figure 4:** L-type transfer function  $|U; IV, IW|$  as frequency-amplitude-diagram: Two data sets (3 spectra each): one taken at the manufacturer site and one during an on-site measurement (power transformer 241 / 110 / 16.5 kV, 50 Hz, 160 / 160 / 53.3 MVA, YNyn0, YNd5).

The measurements have been executed before and after the transportation from the manufacturer to on-site. Without a geometrical change, the measurements can hardly be distinguished. Compared to this, the difference between the phases is much more significant.

### 3. Presentation and evaluation of FRA-measurements

As an experience of our practical examinations, we suggest a representation of the measured transfer functions as a locus plot in the complex plane. It can be stated that in this parameter representation a small change of the transfer function appears indeed more imposingly, than in the conventional frequency curve representation. The reason is that in the conventional amplitude representations, the resonances (poles and zero points) of the transfer function appear only as narrow peaks. However at these points, significant changes in the phase occur, which don't appear in the amplitude representation. In the complex locus plot representation, resonance points develop into loops, the diameter of which changes conspicuously corresponding to the amount of amplitude variation. Thus even small change in the resonance quality factor can easily be recognized.

At the other hand horizontal straight sections of the frequency spectrum without information shrink to a single point and do not occupy large areas of the plot.

A comparison of spectrum and locus plot for the three coupling types corresponding to the definition in section 2 is given in figure 5. It can be recognized that intricate parts of the spectrum are represented clearly in the locus plot. Figures 6 and 7 demonstrate further, that the high frequency part with narrow resonance points can still be reproduced. Thus the locus plot is very helpful as a complement for the spectrum representation highlighting supplementary information.

In order to establish an unambiguous record, the insertion of frequency markings is highly recommended. The markings serve as indicators for a frequency shift of a resonance location.

Our investigation have lead to the following important finding: Since the locus trace of several resonance circuits (main and side resonances) always overlap, the frequency displacements are easily recognized by the shift of two loops against each other. The presumption, that frequency information would be lost in the locus representation has possibly been the reason, why the locus representation has attracted too little attention until now.

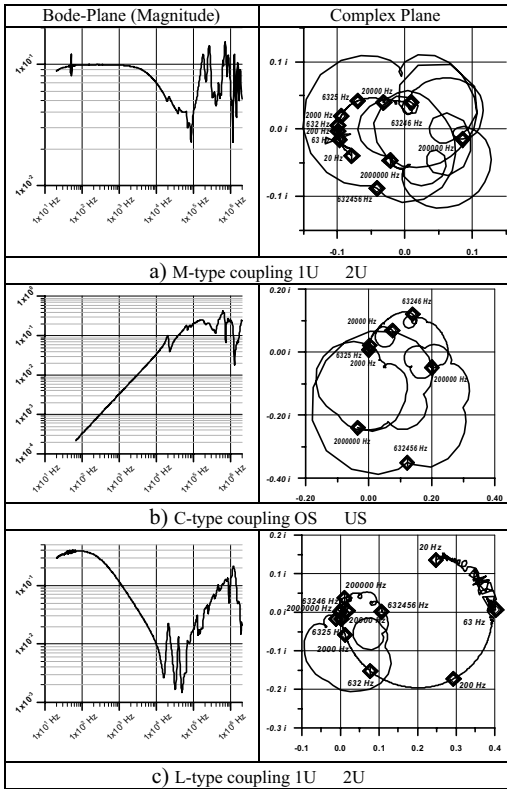


Figure 5: Three examples of FRA measurement represented as frequency spectrum and as locus plot in the complex plane.

#### 4. Conclusions

Amongst other methods for the condition assessment of transformers, the frequency domain FRA measurement, as a practical and quick procedure, focuses to changes in the geometry of the active part (i.e. the conductors, windings and geometry of other metallic parts).

FRA is a comparative method and bases always on a forgoing reference measurement.

Although there are geometrical changes, which do not result in a significant alteration in the transfer function, the method has great popularity, because many relevant faults can be detected or confirmed without a costly opening of the transformer tank.

Advantages of measurements with the terminals loaded with an impedance of 50 have been discussed.

It has also been explained, how in many cases the locus plot in the complex plane exhibits a better sensitivity to small changes of the transfer function than the conventional frequency spectrum and is therefore favourable for the comparison of different measurements.

#### 5. Acknowledgement

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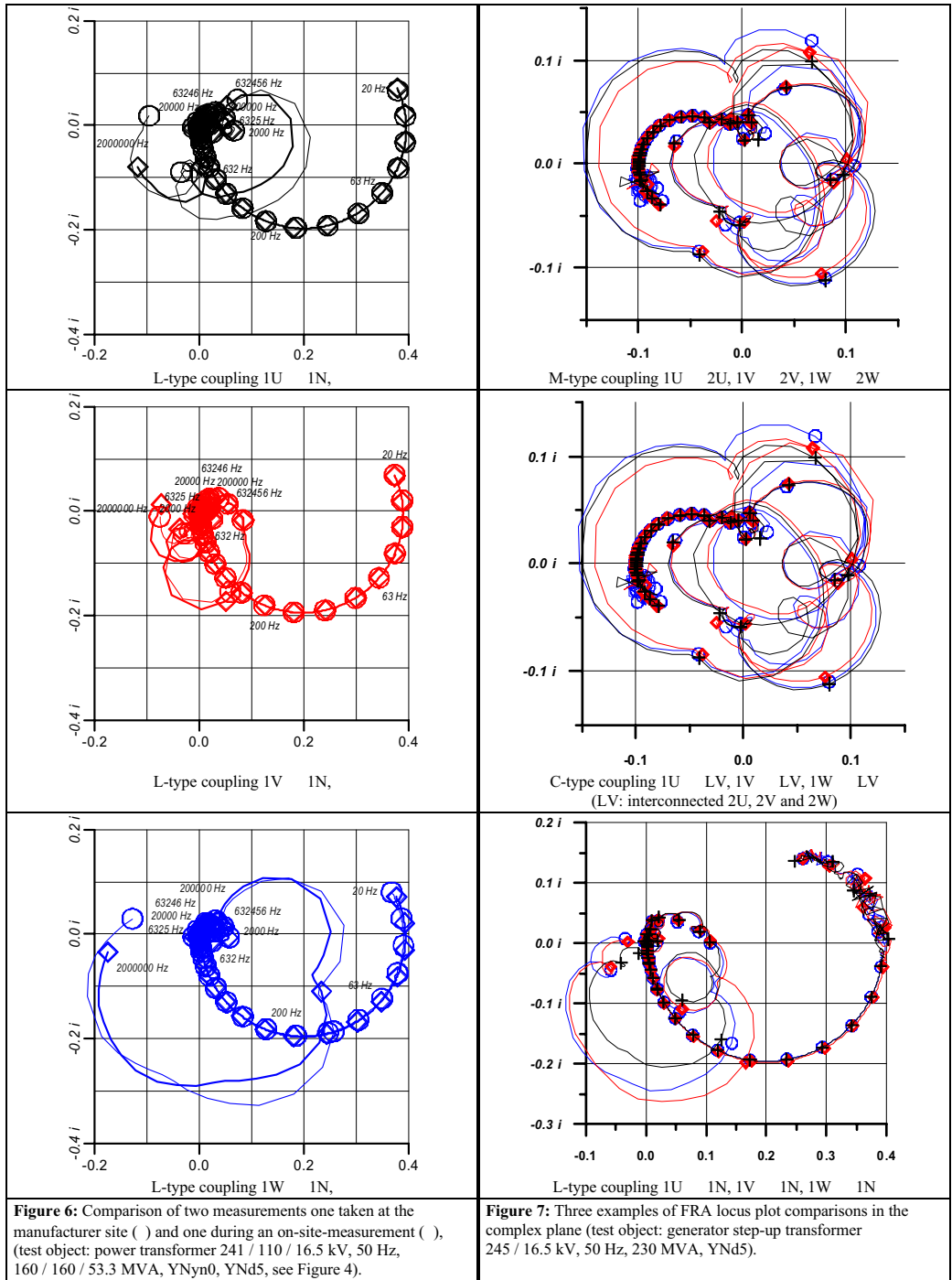
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**Figure 6:** Comparison of two measurements one taken at the manufacturer site (  $\circ$  ) and one during an on-site-measurement (  $\square$  ), (test object: power transformer 241 / 110 / 16.5 kV, 50 Hz, 160 / 160 / 53.3 MVA, YNyn0, YNd5, see Figure 4).

**Figure 7:** Three examples of FRA locus plot comparisons in the complex plane (test object: generator step-up transformer 245 / 16.5 kV, 50 Hz, 230 MVA, YNd5).