High Resolution Frequency Response Analysis (FRA) on Power Transformers by Step Impulse Excitation in 2-pole connection

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Abstract

The paper describes an improved method for measuring the frequency response of power transformers or electrical networks by impulse excitation with help of a specially designed combination of impulse generator and transient recorder. For reducing the basic and quantization noise significantly an averaging technique is implemented. To reduce the influence of test set-up details the test object is connected only with two wires as a 2-pole to the step voltage impulse generator without additional external measuring lines and shunts.

Introduction

The Frequency Response Analysis (FRA) on power transformers is used for diagnosis at works, after putting into operation and for maintenance on site /1,8/. The frequency-dependent admittance is determined and recorded as fingerprint. The FRA taken before and after a transport should show no differences, otherwise a movement e.g. of a winding must be assumed. Because small movements results in very small deviations in the FRA lapse, the measurement method must be very stable and sensitive.

Actually two methods for measurement the frequency response are used:

1. measured with a Network Analyser and sinusoidal excitation sweeping trough all frequencies,
2. measured with a transient recorder and STEP voltage excitation comprising all frequencies at once.

Both are equivalent methods /1/ and show comparable results in case of a comparable test set-up.

The measurement with the network analyser has several problems with reflection-free connection of the coaxial lines to the test object and amplitude scaling of different frequency ranges. The method needs time to sweep through all frequencies of several frequency ranges.

The application of the step response method gives a complete measuring result after applying the STEP voltage and calculating the frequency-dependent admittance with help of the frequency spectra of voltage and current lapse determined by the fast Fourier transform (FFT).

The measurement of the applied step voltage and the current e.g. in the neutral with help of a measuring shunt together with long measuring lines is difficult and may influence the test result.

The basic noise and the quantization noise are limiting the dynamic range of the resulting admittance especially at higher frequencies /1/.

The paper describes an improved test system, which allows precise scaled, and reproducible FRA measurements over a wide frequency range from some Hz to some MHz.

Statements for diagnosis on transformers can be found in /2,3,4/ but are not subject of this paper.

1. Testing Method

The Frequency Response Test System was designed for direct measurement of the frequency behaviour of transformer windings with the step voltage method.

The test object is connected as a 2-pole to the step voltage impulse generator RIG 1000 with up to 1000 V peak voltage and sufficient energy without additional measuring lines and shunts.

Voltage and current are picked directly at the step voltage generators output and therefore not subject of variation of external connections.

This is an important advantage especially for on-site tests after shipping or for maintenance, because of the easy connection reproducible measurements can be expected.

The output voltage and the respective current are recorded with help of a special designed transient recorder TR-AS 25-12 with a basic resolution of 12 Bit at 25 MS/s maximum sampling rate, an adapted bandwidth of 5 MHz and minimized noise of 0.013% (type test).

The basic resolution of 12 Bit is improved by a repetitive averaging technique accumulating a number of voltage and current records phase-equivalent in the time domain.

Depending on the number of accumulations, resulting resolutions up to 32 Bit are reached with a significant reduced noise.

For e.g. 16 accumulations 16 Bit resolution and for 1024 accumulations 26 Bit resolution are resulting.

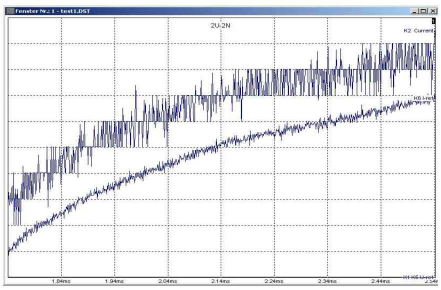

Fig. 1: current lapse in the time domain, zoomed 400x vertically up to 0.025% per div.
upper trace: single shot with 12 Bit resolution
lower trace: 16 accumulations with 16 Bit resulting resolution

The figure shows the improvement of vertical resolution and the reduction of noise by accumulation very clearly.

The voltage and current signals are transformed into the frequency domain using the fast Fourier transformation FFT and then the calculation of the admittance follows.

The voltage and current lapse in the time domain as also the calculated admittance in the frequency domain are displayed on the colour graphic screen of the measuring system.

The measured and calculated date will be stored to the integrated database on the hard disk and a test record can be printed.

2. Test Results

The following pictures show examples of FRA taken on discrete networks as also on power transformers calculated from single shots and from accumulated raw data measured with the averaging method.

2.1 FRA on a discrete Network

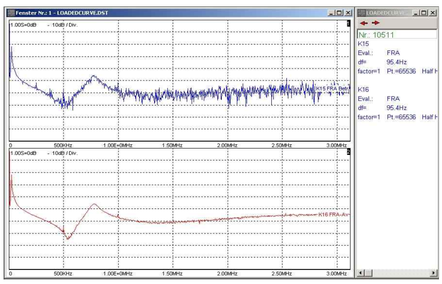

Fig. 2: FRA of a complex network (6,25 MS/s)
frequency span 95,4 Hz, vertical 10 dB/div.
upper trace: single shot with 12 Bit raw data
lower trace: 105 accumulations corresponding to 18 Bit resolution in the raw data

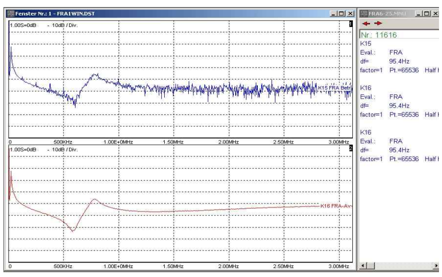

Fig. 3: FRA of a complex network (6,25 MS/s)
frequency span 95,4 Hz, vertical 10 dB/div.
upper trace: single shot with 12 Bit raw data
lower trace: 1024 accumulations corresponding to 22 Bit resolution in the raw data

The FRA calculated with 22 Bit raw data show vertically a dynamic range of 72 dB and up to the Nyquist frequency of 3,125 MHz no significant noise.

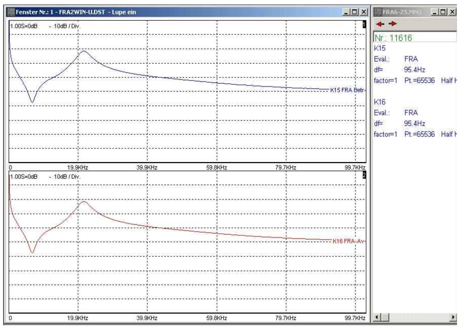

Fig. 4: FRA of a complex network (6,25 MS/s)

frequency span 95,4 Hz, vertical 10 dB/div.

upper trace: single shot with 12 Bit raw data

lower trace: 1024 accumulations corresponding to 22 Bit resolution in the raw data

For lower frequencies, the accumulation does not improve the FRA result significant.

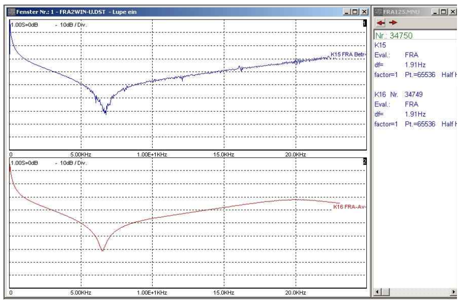

Fig. 5: FRA of a complex network (125 kS/s)

frequency span 1,9 Hz, vertical 10 dB/div.

upper trace: single shot with 12 Bit raw data

lower trace: 64 accumulations corresponding to 18 Bit resolution in the raw data

The fig. 5 recorded with 125 kS/s show a higher dynamic range of the first parallel resonant frequency at approx. 6,6 kHz of –70 dB than fig. 4 recorded with 6,25 MS/s with only -58 dB.

The series resonant frequency at approx. 21 kHz recorded with 125 kS/s respectively 6,25 MS/s has exactly the same magnitude of –22 dB in both figures.

This shows that at least two measurements with different sampling rates respectively frequency spans are necessary to get successful results for all frequencies.

The FRA with 125 kS/s show the admittance with a frequency span of 1,9 Hz down to the D.C. admittance of approx. –10 dB corresponding to 0,43 S or 2,3 Ohm (with 0 dB corresponds to 1 S in fig. 5).

The D.C. value matches the measurement with an Ohmmeter with 2,1 Ohm quite well.

2.2 FRA on Power Transformers

The following examples show measurements on a distribution transformer to examine the test method on a larger network and to analyse the influence of different connection wire length.

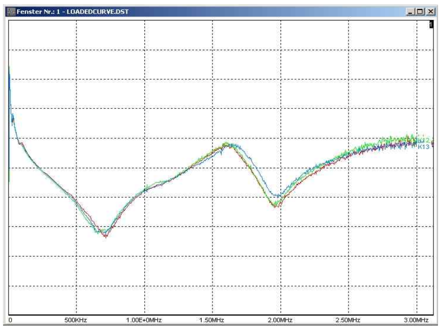

Fig. 6: FRA on the low voltage winding of a 630 kVA distribution transformer, phases 2u, 2v, 2w with respect to 2N, 16 times accumulated with 6,25 MS/s from d.c. up to the Nyquist frequency of 3,125 MHz, the frequency span is 95,4 Hz. The vertical dynamic range is more than 70 dB.

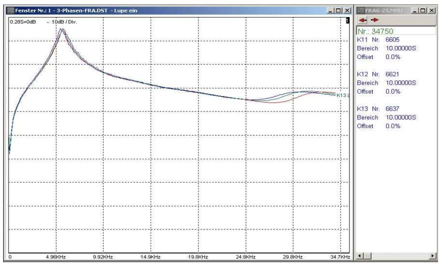

Fig. 7: same as figure 6, displayed from D. C. to 35 kHz only to show lower frequencies

The three phases show nearly identical FRA.

2.3 Influence of Connection Wires

The influence of the length of the connection wires was measured on a relatively small distribution transformer,

In case 1, the shortest length was approx. 1 m and the respective area between both wires was approx. 1 m².

In case 2, the active wire was increased to 2 m and the respective area was approx. 1,5 m².

The influence of the increased inductivity of this loop can be seen significantly for higher frequencies above 0,5 MHz in the FRA.

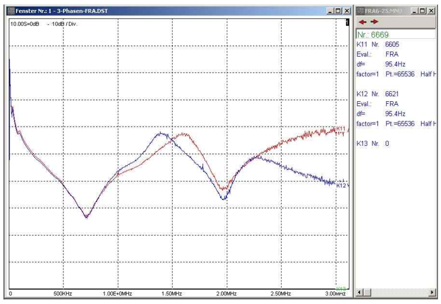

Fig. 8: Influence of the length of the connection wires between STEP voltage generator and terminals. For the lower trace the length was increased by 1 m only, the series resonance frequencies are moving significant while the parallel resonant frequencies are fixed.

This effect must be considered especially at big power transformers with dimensions of some Meters between bushings and ground. To get comparable results the loop area should be minimized and must be described in the test report clearly.

3. Conclusion

The Frequency Response Analysis (FRA) on power transformers for diagnosis will get an established technique in future.

The developed FRA test system comprising all necessary components like step voltage generator, transient recorder and sensor equipment in a compact designed housing.

The easy connection of the test object as 2-pole allows easy and reproducible performance of the FRA.

The phase-synchronous averaging technique improves the signal to noise ratio of the recorded data significant corresponding to 20 and more Bit.

The calculated FRA therefore has a high dynamic range of about 60 to 80 dB up to 5 to 10 MHz without distortions by noise.

The frequency span settable from 1 Hz up to 381 Hz allows analysis in two frequency ranges from D.C. to 12,5 MHz with two measuring cycles only.

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