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Making Frequency Response Analysis Measurements: A Comparison of the Swept Frequency and Low Voltage Impulse Methods

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Abstract: This paper compares the swept frequency (SFM) and low voltage impulse methods (LVI) for making frequency response analysis measurements. The principles of these measurements are explained. Practical examples of the application to a 30MVA transformer with simulated mechanical and electrical faults are presented. For mechanical faults neither method is very successful, but this probably because the simulated fault was not severe enough. For electrical faults the swept frequency method gives better results because it has a finer resolution at low frequencies. In a final comparison of the two methods the swept frequency method is found to be superior in most respects, but the low voltage impulse method is found to have some important advantages.

1. Introduction

Frequency Response Analysis, generally known within the industry as FRA, is a powerful diagnostic test technique. It consists of measuring the impedance of the transformer windings over a wide range of frequencies and comparing the results of these measurements with a reference set. Differences may indicate damage to the transformer, which can be investigated further using other techniques or by an internal examination.

There are two ways of injecting the wide range of frequencies necessary: one can either inject an impulse into the winding or make a frequency sweep using a sinusoidal signal. The former is known as the low voltage impulse method and the latter as the swept frequency method. Both methods are currently used within the industry.

This paper presents a comparison between the two methods for making FRA measurements.

2. Transformer Used for Measurements

All of the measurements presented in this paper were made on a 132/11.5kV, Dzn10, 30MVA power transformer. The experiments were made with the OLTC, bushings and tank removed. In service the HV winding of the transformer is normally connected in delta, but the delta was broken for the experiments.

Faults were simulated on the HV tap winding, which was located at the outside of the winding assembly and was therefore accessible. The HV tap winding was of the multi-start layer type, with ten starts of twelve turns each.

3. Swept Frequency Method (SFM)

As was mentioned earlier, the swept frequency method (SFM) for making FRA measurements injects the wide range of frequencies required by making a frequency sweep using a sinusoidal signal. The sinusoidal signal is generated using a network analyser, which is also used to make the voltage measurements and manipulate the results. The most commonly used measurement circuit is shown in Figure 1.

In Figure 1 S is the injected signal and R and T are the reference and test measurements, Z_S is the source impedance of the network analyser and Z_T is the impedance of the winding under test. The source impedance of the network analyser is always 50Ω.

Note that using the swept frequency method only one set of measurements can be made at once. The time taken by the analyser to sweep the required frequency range depends on how much filtering or averaging is used, but typically varies from a little under one minute to perhaps ten minutes.

In the case of the measurements presented in this paper, the resolution of the measurements varied across the frequency domain, but in the useful part of the spectrum (above 250Hz) it was 2% or better.

The measurement results are conventionally presented in modulus-argument form. The modulus is usually called the amplitude or gain and the argument the phase.

Using the same notation as Figure 1, the amplitude is defined by:

$$k = 20\log_{10}(T/R) \qquad (1)$$

Again using the same notation as Figure 1, the phase is defined by:

$$\phi = \angle(T/R) \qquad (2)$$

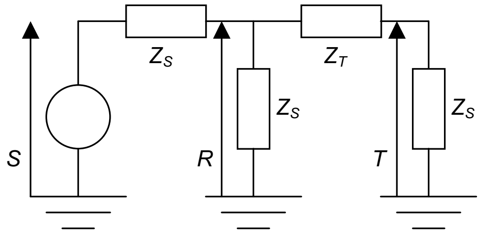

Figure 1: Basic measurement circuit

The measurements presented in this paper were made with all non-tested terminals at floating potential. Broadband noise was removed by using a narrow band filter. This measurement method is the *de facto* industry standard for the swept frequency method.

4. Low Voltage Impulse Method (LVI)

As was mentioned earlier, the low voltage impulse method (LVI) for making FRA measurements injects the wide range of frequencies required as a voltage impulse into one terminal. The voltage at another terminal or the current passing through the winding connected to the terminal or any of the other windings is measured. It is possible to measure several currents and voltages simultaneously. The signals are filtered, sampled and stored in the time domain. They are then transferred to the frequency domain and the transfer function is calculated.

During the experiments on the 30MVA transformer, the impulse generated by a 500 V impulse generator was applied to the HV line terminal and the current in the HV neutral and the voltage transferred to the LV line terminal were measured. For measuring the neutral current, a Rogowski-coil is used. The signals are filtered at a cut-off-frequency of 2.1 MHz, sampled at 10 MS/s with a resolution of 10 Bit and a storage of 15000 samples. The frequency spectrum was calculated using an FFT with 4096 samples. The resulting resolution in the frequency domain was 2.44kHz.

The results were used to deduce two different transfer functions, one between the HV current and the applied voltage and the other between the transferred voltage and the applied voltage. Mathematically, these are defined as follows:

$$TF_1(f)=\frac{I_N(f)}{U_A(f)} \tag{3}$$

$$TF_2(f)=\frac{U_T(f)}{U_A(f)} \tag{4}$$

where U_A is the applied voltage, I_N is the neutral current and U_T is the transferred voltage.

5. Measurement Results

Mechanical fault

Detecting mechanical damage to transformer windings is one of the main interests of FRA. Mechanical deformation was simulated by adding additional inter-turn separators to the HV tap winding, which was the only accessible winding.

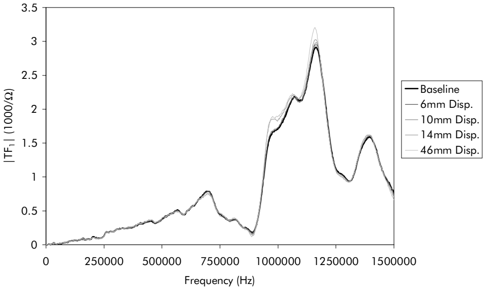

Figure 2: $|TF_1|$ with simulated mechanical fault (LVI). (Note linear frequency scale from 0Hz to 1.5MHz).

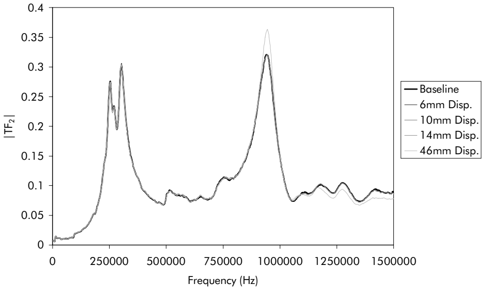

Figure 3: $|TF_2|$ with simulated mechanical fault (LVI). (Note linear frequency scale from 0Hz to 1.5MHz)

The results of the FRA measurements made using the low voltage impulse method are shown in Figures 2 and 3.

Some changes to TF_2 seem to be apparent around 1MHz. It is believed that these changes are caused by natural variation rather than by the simulated mechanical fault. Some changes remained even when the winding was returned to its original position.

The results of the FRA measurements made using the swept frequency method are shown in Figure 4.

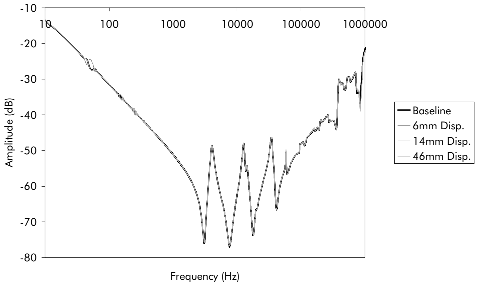

Figure 4: Amplitude with simulated mechanical fault (SFM). (Note logarithmic frequency scale from 10Hz to 1MHz).

There are no significant changes in the SFM results either. The non-diagnosis of the fault can be explained partly by the fact the fault was simulated on the tap winding, which links less flux than the main windings, and partly by the fact that only winding displacement, and not winding damage was simulated. It should also be pointed out that the largest displacement simulated was only about 3% of the window height. The smallest displacement of a main winding which can normally be detected by FRA, using either LVI or SFM, is about 2% of the window height [1]. It is therefore not surprising that displacing half the tap winding through 3% of the window height should be difficult to detect.

These tests are rather unrealistic and do not call into question the ability of FRA to detect mechanical faults in general.

Electrical fault

A short-circuit was simulated by connecting two adjacent turns in the tap winding.

The results of FRA measurement using the impulse response method are shown in Figures 5 and 6.

There is no significant difference visible in Figures 5 and 6 between the results with and without a short-circuit. The small differences which are visible are owing to natural variation.

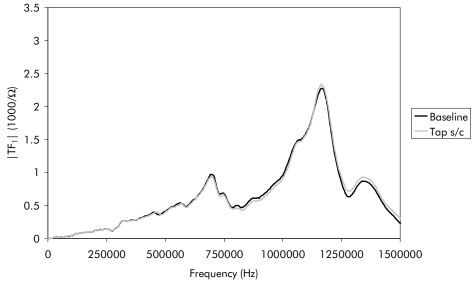

Figure 5: $|TF_1|$ with simulated electrical fault (LVI). (Note linear frequency scale from 0Hz to 1.5MHz).

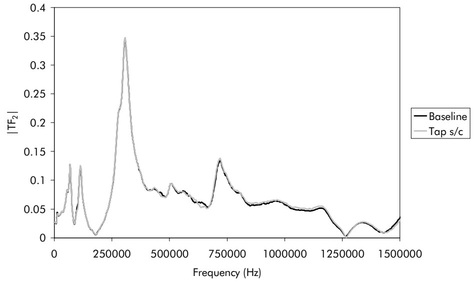

Figure 6: $|TF_2|$ with simulated electrical fault (LVI). (Note linear frequency scale from 0Hz to 1.5MHz).

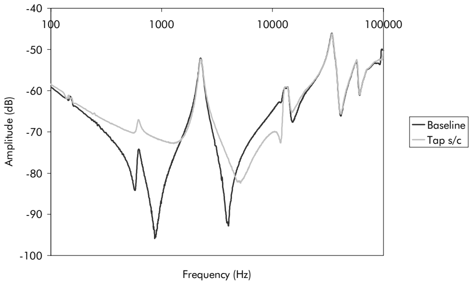

Figure 7: Amplitude with simulated mechanical fault (SFM). (Note logarithmic frequency scale from 100Hz to 1MHz).

The results of the FRA measurements made using the swept frequency method are shown in Figure 7.

There are significant differences between the FRA results with and without the short-circuit from about 100Hz to about 20kHz. The resonant frequencies are shifted and there is a large increase in the amplitude.

The resolution in the frequency domain of the low voltage impulse method measurements is limited to 2.44kHz. This results in only a very small number of data points in the frequency range affected by this fault, which it impossible to diagnose.

6. Direct Comparison of Results from the Two Methods

The modulus of the impedance can be deduced from the results of FRA measurements using each of the two methods. For the swept frequency method it is given by:

$$Z_T = Z_S\left(10^{-k/20} - 1\right) \quad (5)$$

Similarly for the LVI method it is given by:

$$Z_T = 1/TF_1 \quad (6)$$

The results of FRA measurements no fault simulated using the two methods are shown in Figures 8 and 9.

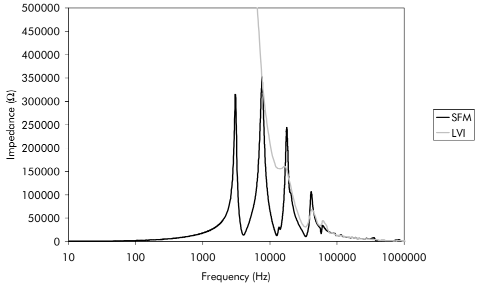

Figure 8: Impedance as measured using SFM and LVI. (Note logarithmic frequency scale from 10Hz to 1MHz).

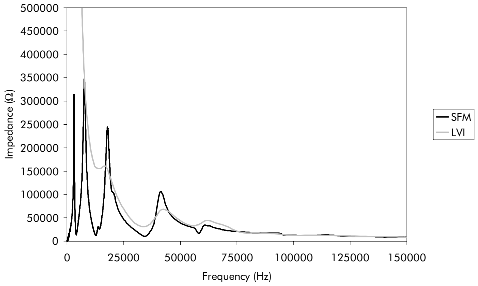

Figure 10: Impedance as measured using SFM and LVI. (Note linear frequency scale from 0Hz to 150kHz).

There are some differences in the results. These are caused both by the limitations of the test methods and the calculations used to process the results. The different resolutions of the frequency domain do not allow comparisons for frequencies lower than 10 kHz. For frequencies higher than 10 kHz results from the LVI method are not similar but comparable with the results of the swept frequency method. This is encouraging for both methods.

7. Conclusions

The low voltage impulse method (LVI) has the following main disadvantages:

- The frequency resolution is fixed, and at low frequencies is poor. This makes it difficult to detect electrical faults.
- It is difficult to filter out broadband noise.
- The amount of power injected into the test object is different at different frequencies. This leads to differences in precision across the frequency range.
- Several pieces of measuring equipment are required (function generator, digital oscilloscope, Rogowski coil).

The LVI method has the following main advantages:

+ Several transfer functions can be measured simultaneously.
+ The time taken to make each measurement is typically about a minute.

The swept frequency method (SFM) has the following main disadvantages:

- Only one measurement can be made at a time. Simultaneous determination of more than one transfer function is not possible.
- The time taken to make each measurement is typically several minutes.

The swept frequency method (SFM) has the following main advantages:

+ High signal to noise ratio. This comes from using the filtering function of the network analyser to remove broadband noise.
+ A very wide range of frequencies can be scanned.
+ It is possible to use a finer frequency resolution at low frequencies. Alternatively, the frequency resolution can be adapted to the frequency band being measured.
+ Only one piece of measuring equipment is required.

Both methods are sensitive to the test set-up, particularly the quality of the earthing. The impedance curves determined by both methods are similar but reveal differences due to measurement set-up and calculation algorithms.

8. Acknowledgement

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9. References

[1] Feser K., J. Christian, C. Neumann, U. Sundermann, T. Leibfried, A. Kachler and M. Loppacher, "The Transfer Function Method for Detection of Winding Displacements on Power Transformers after Transport, Short Circuit or 30 Years of Service". CIGRE paper 12/33-04, 2000.