A COMPARISON OF THE SWEPT FREQUENCY AND IMPULSE RESPONSE METHODS FOR MAKING FREQUENCY RESPONSE ANALYSIS MEASUREMENTS

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ABSTRACT

This paper presents the results of a comparison between the swept frequency and impulse response methods for making FRA. Electrical and mechanical faults were simulated on a 30MVA transformer and measurements were made using both methods. For electrical faults the swept frequency method gives better results because it has a finer resolution at low frequencies. For mechanical faults neither method was very successful, probably because the fault simulated was not severe enough. The swept frequency method gave more repeatable results, which is important for avoiding false positives. Overall the swept frequency method is found to be superior in most respects, although the impulse response method does 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 sometimes known as the impulse response 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.

1.1 TRANSFORMER USED FOR THE MEASUREMENTS

All of the measurements presented in this paper were made on a 30MVA 132/11.5kV industrial 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.

2 IMPULSE RESPONSE METHOD

As was mentioned earlier, the impulse response method 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 connecting 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 and sampled and stored in the time domain. They are then transferred to the frequency domain and the transfer function calculated.

During the experiments on the 30MVA transformer, the impulse 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. 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:

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

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

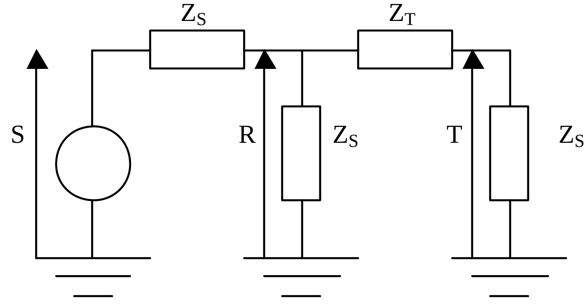
where U_A is the applied voltage, I_N is the neutral current and U_T is the transferred voltage.

For the experiments the injected signal was generated using a 500V function generator. The duration of the applied pulse was 300µs-400µs. The applied and transferred voltages were measured directly using a digital oscilloscope. The neutral current was measured using a Rogowski coil and a digital oscilloscope. They were filtered with a cut-off frequency of 2.1MHz and sampled at 10MHz with 10 bit precision. A total of 15000 samples were stored. The time domain signals were stored in a binary format and the converted to the frequency domain using an FFT. For the FFT 4096 samples were used. The resolution in the frequency domain was 2.44kHz.

3 SWEPT FREQUENCY METHOD

As was mentioned earlier, the swept frequency method 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. A large number of measurement configurations are possible. The most widely used, and the technique used for all the measurements presented in this paper, is to inject a signal at one terminal of a winding and measure the voltage at both ends, with all of the other winding terminals disconnected from one another and ground. This gives rise to the measurement circuit shown in figure 1.

FIGURE 1:
Measurement Circuit Using Swept Frequency Method



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.

For the experiments the narrow-band filtering function of the network analyser was used to improve the signal to noise ratio. The connections were made using screened cables, the screens being grounded at both the network analyser and to the transformer tank. The network analyser was connected to the same ground as the transformer tank, using an isolating transformer.

The swept frequency range for the experiments was from 5Hz to 2MHz, or lower in some cases where the higher frequency measurements were not required. The network analyser used did not support frequency sweeps with logarithmically spaced points, so the five different linear sweeps were made, each with a different spacing. The spacing between points varied, but in the useful part of the frequency range (above 250Hz) the difference between adjacent measurement points was always less than 2%.

There are a number of possible methods of presenting the results of measurements made using the swept frequency method. The most widespread is to plot a graph of the so-called amplitude, as measured by the network analyser, against frequency. Both linear and logarithmic scales are used. The authors prefer logarithmic scales, which are used in this paper.

The so-called amplitude, as measured by the network analyser, is defined by:

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

using the same notation as figure 1.

This amplitude and the impedances are related by:

(4) $$k = 20\log_{10}\left(\frac{Z_S}{Z_S + Z_T}\right)$$

again using the same notation as figure 1.

4 MEASUREMENT RESULTS

4.1 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 2 and 3.

There is no significant difference visible in figure 2 or 3 between the results with and without a short-circuit. The small differences which are visible are owing to natural variation.

FIGURE 2:
FRA Results (Impulse Response Method) with Simulated Short-Circuit Fault

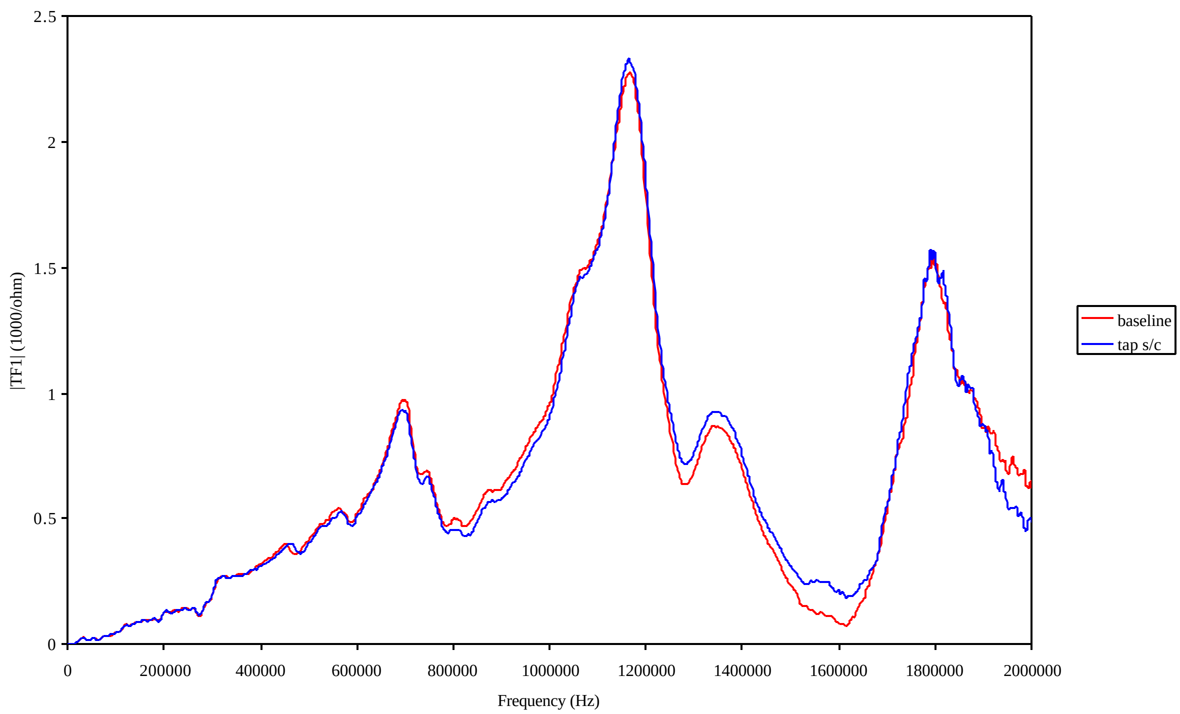


FIGURE 3:
FRA Results (Impulse Response Method) with Simulated Short-Circuit Fault

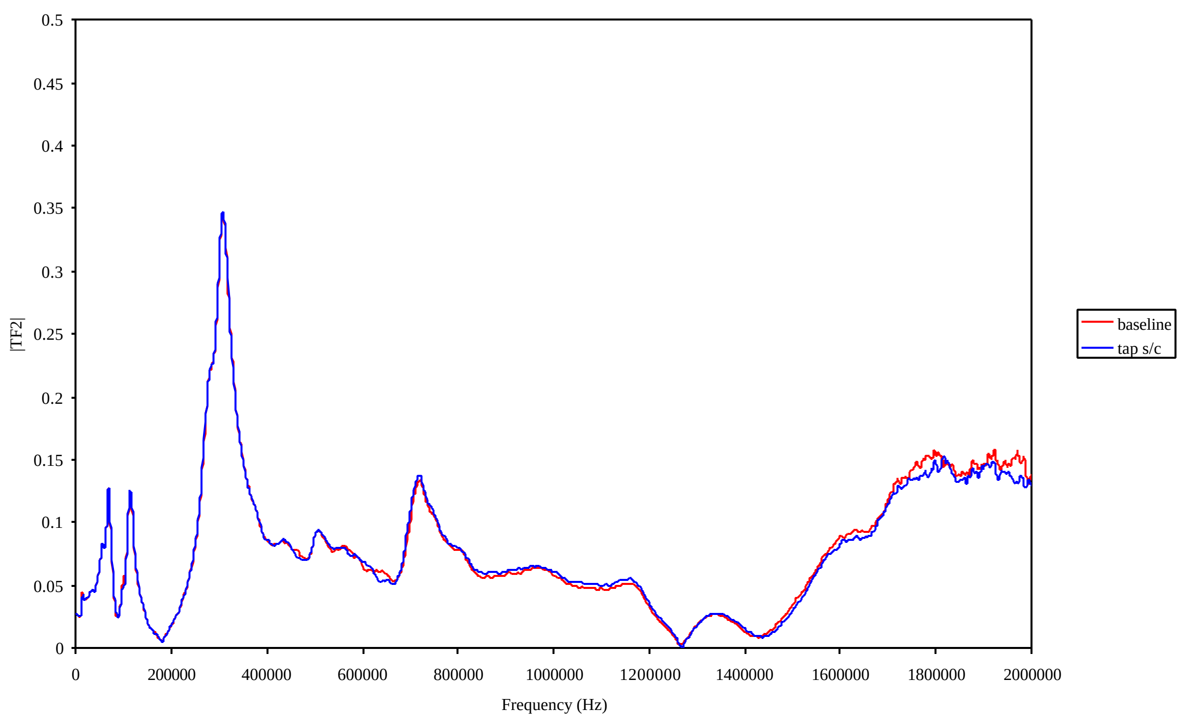
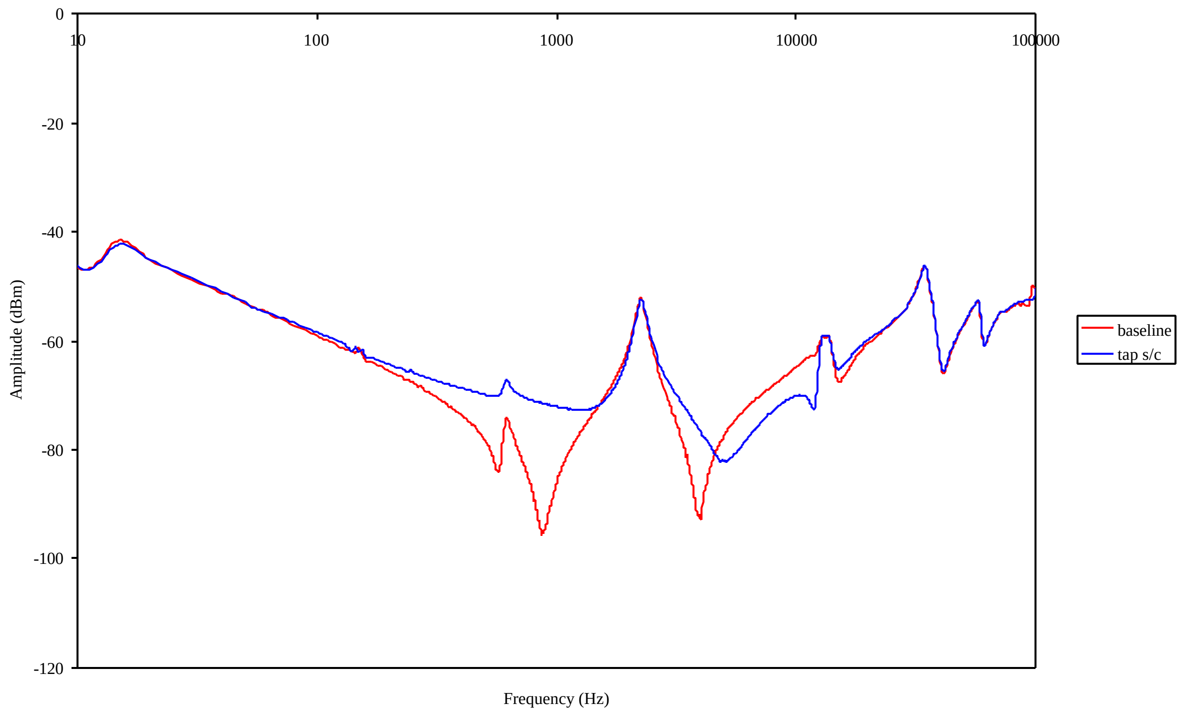


FIGURE 4:
FRA Results (Swept Frequency Method) with Simulated Short-Circuit Fault



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

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 reduction in the modulus of the impedance.

The duration of the impulse used for the impulse response method was 300µs-400µs, this limited the resolution of the data points in the frequency domain to 2.44kHz. Increasing the number of samples in the FFT does not add more information. The result of the low frequency resolution is a very small number of points in the affected frequency range, which makes the fault impossible to diagnose.

4.2 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. Several different thicknesses of additional inter-turn separators were used.

The results of the FRA measurements made using the impulse response method are shown in figures 5 and 6.

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.

FIGURE 5:
FRA Results (Impulse Response Method) with Simulated Winding Displacement

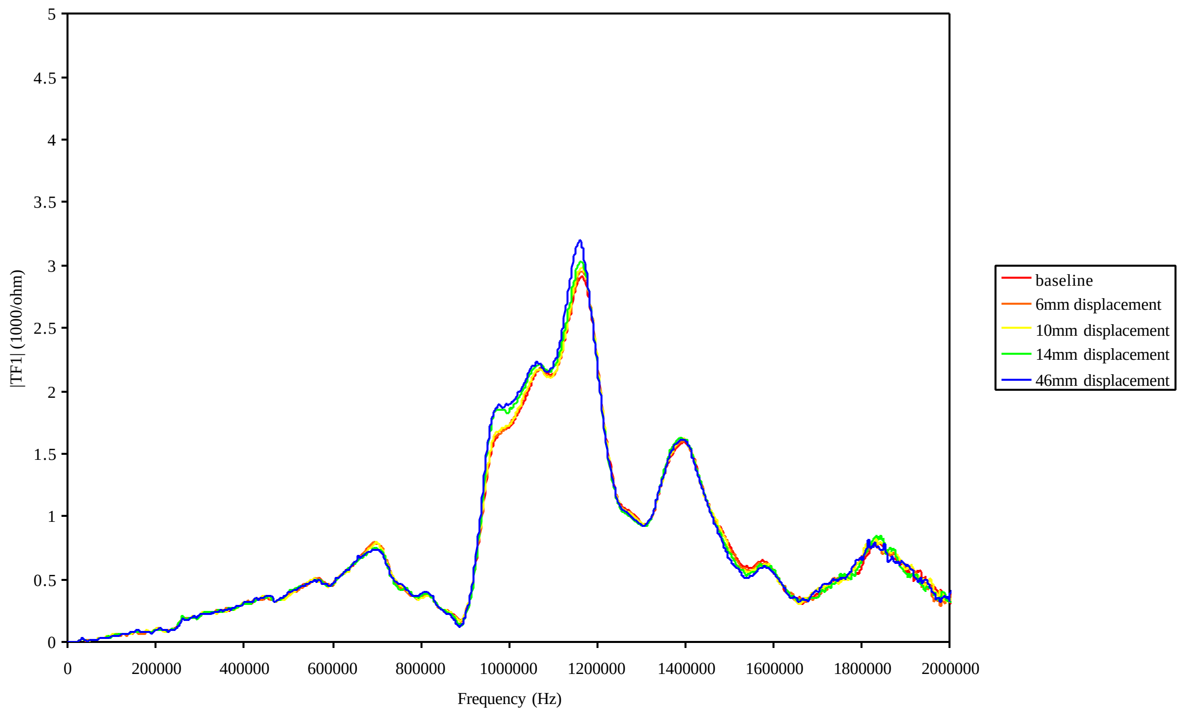


FIGURE 6:
FRA Results (Impulse Response Method) with Simulated Winding Displacement

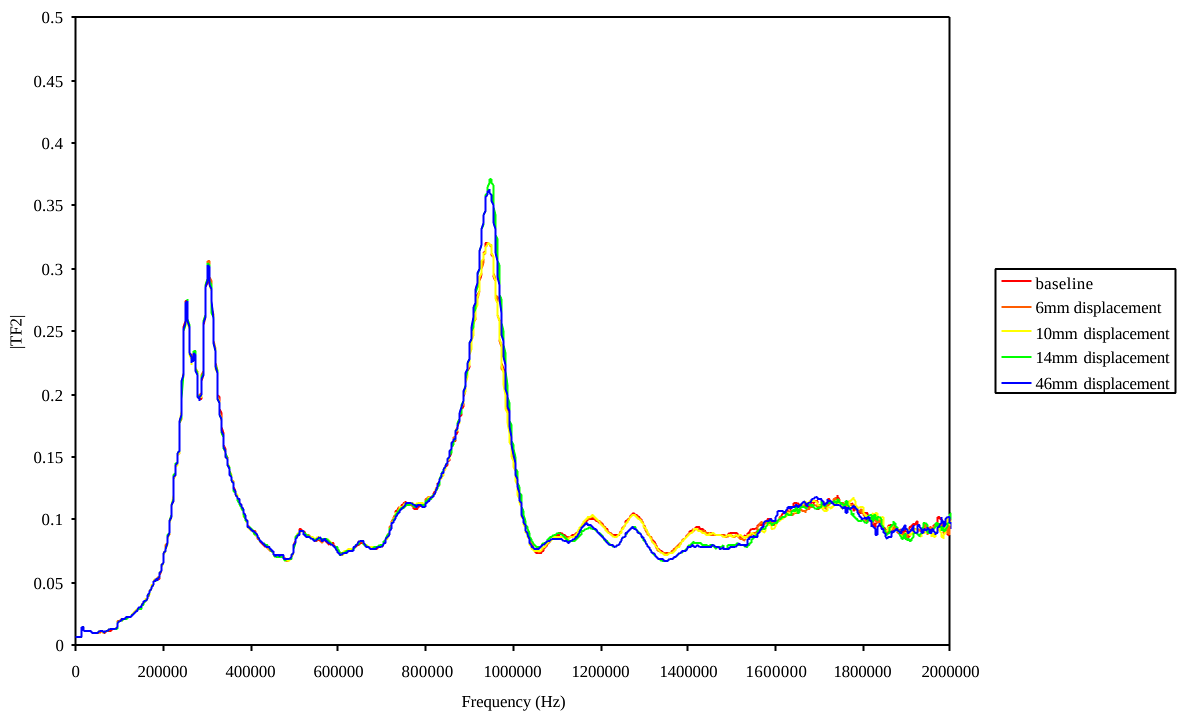
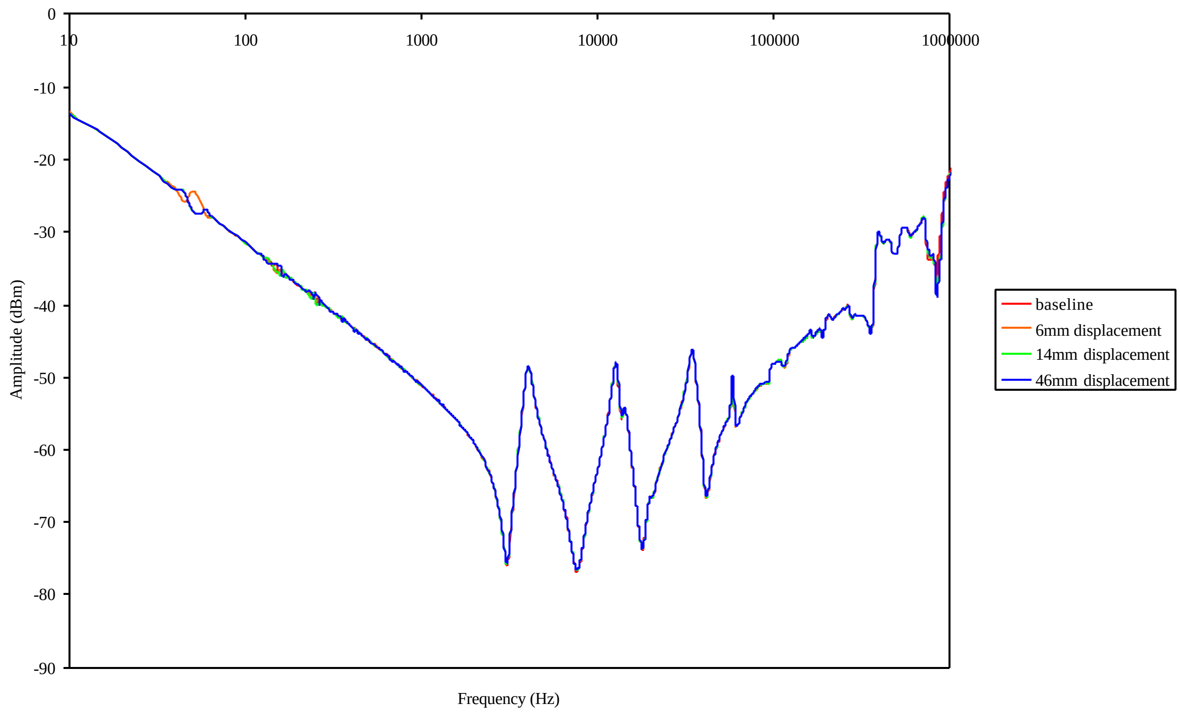


FIGURE 7:
FRA Results (Swept Frequency Method) with Simulated Winding Displacement



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

There are no significant changes in any of the results.

The disappointing results obtained in the mechanical seem to be explained by subsequently published work. It has been shown that the smallest axial displacement of an entire winding which is detectable using FRA is about 2% of the window height. (See reference [1] for further details). The fault simulated here involved moving half of the tap winding through a maximum of 46mm. This is approximately equivalent to moving 15% of the winding through 3% of the window height. It is not very surprising that this fault could not be detected.

4.3 COMPARING RESULTS OF THE TWO METHODS

The results of FRA measurements no fault simulated using the two methods are shown in figures 8 and 9. The results in figure 8 are presented as TF1 using a linear scale for frequency from 0Hz to 2MHz. The results in figure 9 are presented as the amplitude using a logarithmic scale for frequency from 10Hz to 1MHz.

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. Although there are very few results from the impulse response method at low frequencies, they are comparable with the results of the swept frequency method. This is encouraging for both methods.

FIGURE 8:
Comparison of FRA Results Using Two Measurement Methods

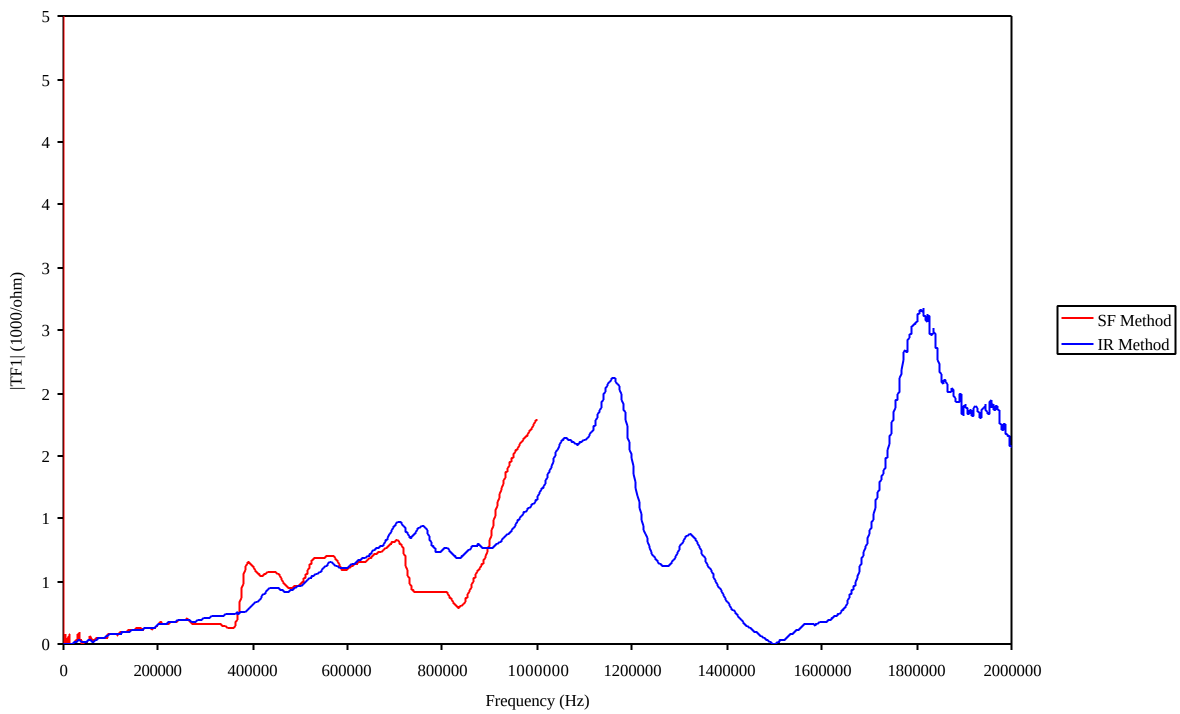
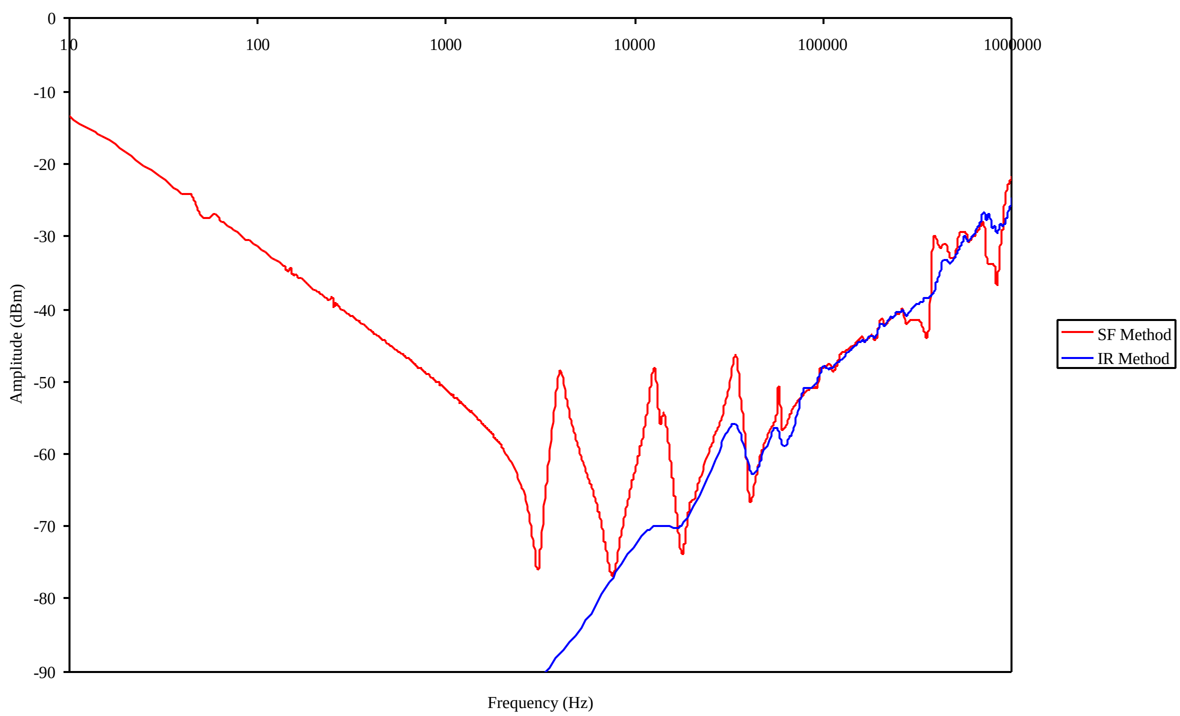


FIGURE 9:
Comparison of FRA Results Using Two Measurement Methods



5 CONCLUSIONS

The authors believe that the swept frequency method 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.

The authors believe that the swept frequency method 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 authors believe that the impulse response 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 authors believe that the impulse response method has the following 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).

Both methods are sensitive to the test set up, particularly the quality of the grounding.

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[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.

BIOGRAPHIES

Simon Ryder was born in England in 1973. He graduated from St John's College, Oxford University, in 1996 with an MEng in Engineering Science. He joined Alstom later that year. He is presently employed as a Research Engineer at Alstom Transformer Research Centre, Saint-Ouen (France). His mains areas of interest are FRA, thermal characteristics of transformers and winding technology.

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Stefan Tenbohlen received his Dr.-Ing. degree from the Technical University of Aachen, Germany, in 1997. He did his doctoral thesis in the insulation behaviour of gas-insulated switchgear. Since 1997 he has been with ALSTOM Schorch Transformatoren GmbH in Mönchengladbach, Germany. He is responsible for the development and design of power transformers and in this function he also works in the field of on- and off-line diagnosis of power transformers.