Reproducibility of Transfer Function Results

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Abstract: The Transfer Function (TF) is a comparative method to monitor the mechanical condition of transformer windings. To perform on-site diagnosis a high reproducibility of TF results is required. Consequently, there are certain restrictions for the determination of the TF using time domain records.
This paper describes the effect of different signal processing procedures on the results of TF calculations. Windowing and pre-triggering are aspects of special interest for the application of the TF method. Additionally, condition parameters of the device under test affect the results of TF measurements. The correlation of transformer temperatures and TF characteristics has been investigated as well as the dielectric effect of the insulating oil and the position of the tap changer. Finally, the effect of different test set-up concepts is presented.

1. Introduction

Mechanical damages in transformers may occur due to high current stress in windings. Such damages do not necessarily lead to an immediate failure of the transformer, but the ability to withstand further mechanical stress becomes reduced. To detect even small deformations and buckling of windings new diagnostic methods are required. One method is the examination of the high frequency transfer behaviour of transformers [1].

The transfer function $\underline{TF}(w)$ is an approximated determination of the Fourier-transformed impulse response $\underline{H}(w)$. For the applied frequency response analysis (FRA) low voltage impulses (LVI) have been used as an excitation. The transfer function $\underline{TF}(w)$ has been determined by the quotient of the Fourier-transformed input signal $\underline{X}(w)$ and its response signal $\underline{Y}(w)$ according to:

$$\underline{TF}(?) = \frac{\underline{Y}(?)}{\underline{X}(?)} \qquad (1)$$

This method is an approach to detect even small changes [2] in transformers by comparing actual test results with a reference measurement. The main restriction for the applicability of this comparative method is a high reproducibility of each TF test. This reproducibility may either be affected by the test arrangement, the test conditions and the procedure of TF calculation. The main objective of this paper is the investigation of the effects to the TF results.

2. Effect of signal processing

Windowing in time domain

Applying the Fast Fourier Transform for a single transient signal implies that the recorded time domain signal is periodic with the period equal to the record length (figure 1).

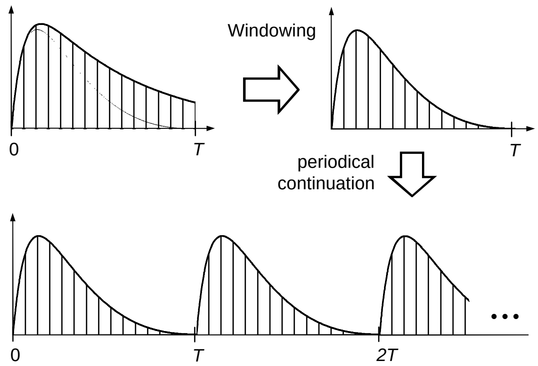

Figure 1: Signal processing for time domain records to eliminate truncation errors for TF results by multiplying a window function

If the tail of the recorded signal has not decayed to zero within the record length *T*, the associated truncation will cause artificially high frequency components to occur in the transformed signal [2]. This problem can be avoided by extending the record window from *T* to 2*T* where the first part of the extended time domain signal is defined by the transient record and the second part consists of a ramp function which tends to zero [2]. A different approach which avoids the doubling of the number of time domain samples is the usage of window functions where the original time record is multiplied by an appropriate function which smoothly approaches zero at $t = T$. Commonly used windows for the purpose of signal windowing are Gaussian, exponential, Hanning, Hamming, rectangular and compositions of Hanning and rectangular. The effect of these commonly used window functions on the results of TF calculations is shown in figure 2.

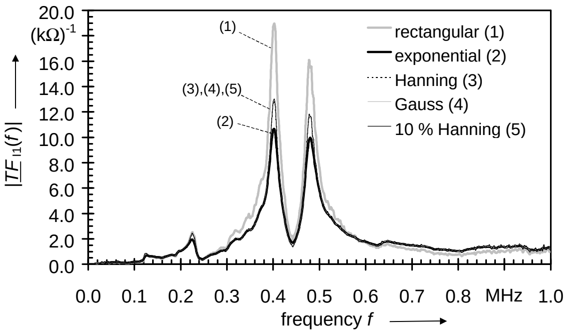

Figure 2: Applying different types of window functions for reducing of truncation errors (input admittance; 17 MVA rectifier transformer)

For the experiment of figure 2 a 0.6/38 µs, 1.2 kV impulse voltage is used as excitation. It is shown that the applied window function reduces the peak value of resonance points while their location is unchanged. The reduction in peak value is strongest for the exponential window function while the effect of the other windows (Gaussian, full Hanning and 10 % Hanning window function) is weaker.

Pre-Trigger

There are certain degrees of freedom to apply signal processing in time domain. It is up to the test engineer to chose the sample length of time domain records and the way to include these samples in signal processing procedure. Figure 3 shows the effect of different pre-trigger lengths on TF characteristics.

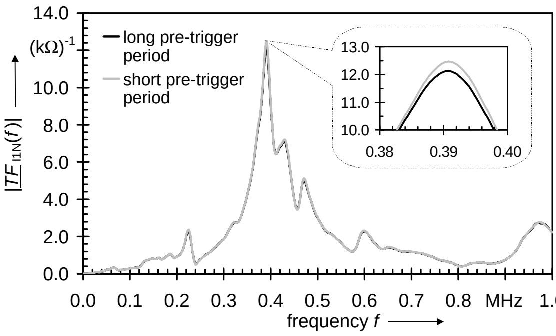

Figure 3: Effect of different pre-trigger sample lengths on TF results (TF of the neutral current; 200 MVA power transformer)

Variations of pre-trigger length result in pure differences of Q-factors of resonance peaks and anti-resonance minima. There is no effect to any characteristic frequency (frequencies of resonance and anti-resonance) .

Another aspect is given by the procedure of pre-trigger periods and multiplication of window functions. The TF results of two different windowing processes are shown in figure 4. The first one includes the pre-trigger period for the multiplication of time domain samples and window function (first sample). The second excludes the pre-trigger samples for this multiplication (instant of trigger).

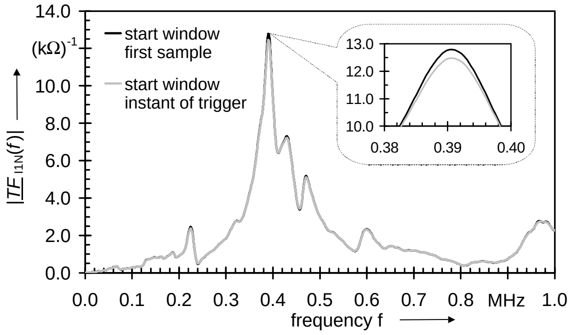

Figure 4: Effect of different procedures of windowing in time domain: windowing inclusively and exclusively pre-trigger period (TF of the neutral current; 200 MVA power transformer)

As it can be seen in figure 4 there is only a weak effect to TF results. For the presented experiment there is a small decay for the dominant resonance peak detectable. Characteristic frequencies are not affected by this variation of signal processing.

3. Effects of condition parameters, test set-up and environmental circumstances

TF results are not only affected by signal processing algorithms. There are also metrological effects caused by the measurement equipment and the test set-up. TF's do not determine exclusively the transfer behaviour of a single test object, but include the behaviour of any sensors and signal wires. Thus, the final result is affected by the set-up of the transformer's terminals, the set-up of neutral wires, the transfer rate of voltage and current probes, the applied tap changer position and the moving direction of the tap changer.

Transfer characteristics of sensors

Sensors are used to convert or to adapt signals for measuring and recording. From the practical point of view even commercially available sensors and monitors (active or passive) do not have an ideal constant transfer ratio for the specified frequency range. Thus, the TF result is affected by the transfer behaviour of any sensors. The current-to-voltage transfer ratio of a commercially available current monitor is investigated in [2]. It is shown, that inductive current monitors do not have an ideal bandpass transfer characteristic. Variations of the signal transfer ratio can be detected even in the specified nominal frequency range. In practice, this means that if such non-ideal sensors are applied, experimentally determined TF's can only be evaluated if the same sensors have been used for the tests or the transfer behaviour of the applied sensor is well-known.

Mounting and set-up of sensors

TF results will be affected by the sensors' transfer behaviour itself as well as the set-up of mounting and connections. There are certain restrictions to minimize such 'parasitic' effects. One basic rule is to avoid any un-shielded signal wires if possible. The effect of the test arrangement if non-shielded lines are used to connect a transformer terminal and a Rogowski-coil is shown in figure 5.

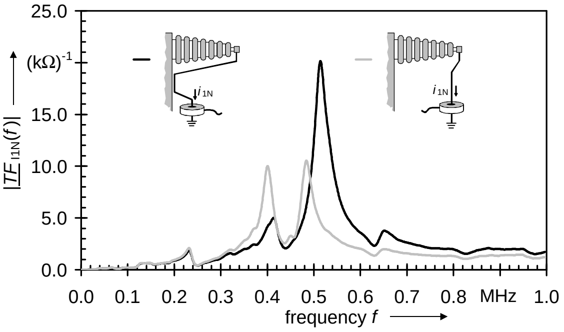

Figure 5: Effect of different set-up concepts for current monitors (TF of the neutral current; 200 MVA power transformer)

Two different lay-out of the current's signal wire result in two totally different transfer functions of the neutral current of the examined power transformer. Any reproducibility is impossible if there is no detailed documentation about the mechanical set-up.

Grounding concept

The coupling of ambient noise to the measured signal has been investigated in [2] for different concepts of grounding. Interference from electric fields can be reduced by using an additional, low inductive grounding wire for the connection of the transient recorder and the reference neutral. Interference from magnetic fields can be reduced by making the loop between the ground wire and the coaxial cable's shield as small as possible. Therefore, all coaxial wires should be located as close as possible to the neutral ground. If the induced magnetic field noise becomes dominant over electric field noise it is recommended not to use the additional ground wire.

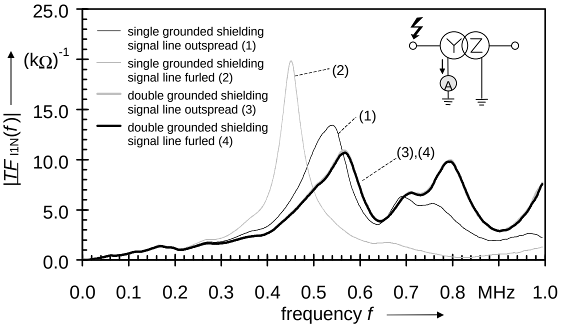

Figure 6: Effect of different grounding concepts for signal line shielding (TF results of the neutral current; 150 kVA, Yz-distribution transformer)

If the power supply neutral of the transient recorder is chosen as reference, it is obligatory to connect the shield at both terminals to neutral ground. As it is shown in figure 6 a single connection of shields will result in transfer function results which are affected by the location of the coaxial wires. Consequently, this concept is not practical for on-site measurements. If the transformer's tank is chosen as reference neutral, a grounding of the shields at the test object's terminals is sufficient to avoid this kind of disturbance.

Condition parameters of test objects

Some condition parameters of test objects take a strong effect on TF results. For power transformers the applied tap changer position and the thermal condition of the winding are the most important parameters. Additionally, the dielectric properties of any insulation fluid will take effect on characteristics of transformers' transfer functions.

Dielectric medium

For on-site diagnoses actual transfer functions are compared to fingerprint results of former times. Sometimes, fingerprints are recorded just before transportation in the factory. Thus these assemblies have been examined without insulation liquid. For transportation, transformers are filled with nitrogen or synthetic air. The effect of different dielectric media (oil and air) is shown in figure 7.

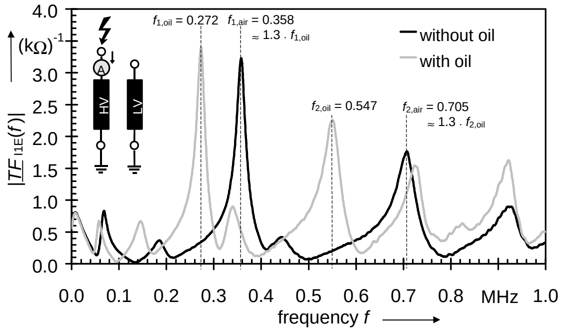

Figure 7: Effect of different dielectric media (input admittance of a coil assembly; 1 MVA distribution transformer.)

According to the theory there is a systematic shift of characteristic frequencies due to the dielectric behaviour of oil. The ratio between both frequency scaling has been determined to 1.3 and corresponds approximately to the square root of the relative dielectric permittivity of mineral oil $(e_{\mathrm{r,oil}})^{½}$.

Temperature of oil and coil assembly

Thermal conditions of transformers are directly related to its immediate load history. TF characteristics (damping rates and resonance frequencies) are influenced by thermal conditions of the dielectric medium and the conduction of the coil. Any restrictions for the comparability of TF results because of unequal temperatures have been investigated in laboratory. The results are shown in figure 8.

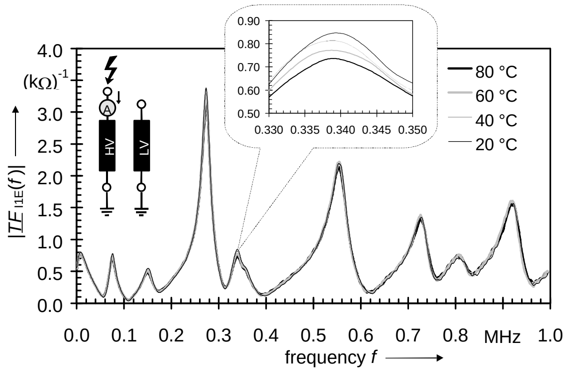

Figure 8: Effect of different temperatures on TF results (input admittance of a coil assembly; 1 MVA distribution transformer)

TF measurements at a test winding during a cooling-down period from 80 °C to 20 °C imply a thermal coefficient for resonance and anti-resonance frequencies of $-2.6 \cdot 10^{-5}$ K^{-1}. The thermal shift of coil Q-factors is about $-2.7 \cdot 10^{-3}$ K^{-1}. In practice, the span of oil temperatures for on-site tests (after switch-off and installation of the test set-up) ranges from 15 °C to 70 °C. Due to the small coefficients, it is in practice not necessary to make a correction as the effect of different temperatures disappears in the uncertainty range of the limited measuring accuracy [2].

Applied tap changer position

Each position of the tap changer leads to a different transfer behaviour. The propagation of the TF characteristics due to the movement of the tap changer has been investigated for a real power transformer. Figure 9 shows the setting of the tap changer contacts and terminals for different voltage transfer ratios as well as a different history of switching process.

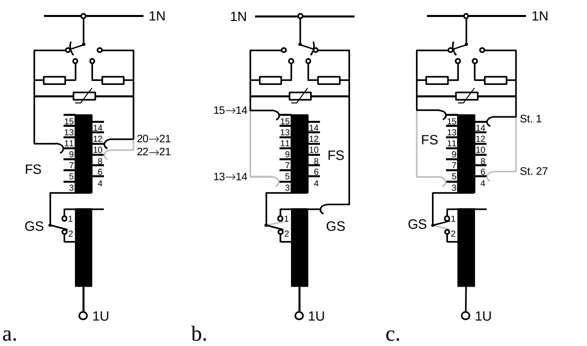

Figure 9: Mechanical configuration for different applied tap positions of an on-load tap changer (OLTC): 27 taps

a. position 21 for up and down direction of movement
b. nominal tap position for both directions of movement
c. margins of voltage regulation: position 1 and 27

As it is shown, the setting of the non-loaded tap of the tap selector depends on the position which has been chosen before. Consequently, the history of movement (direction of movement which have lead to the actual position) takes effect on the results of TF's as well as the chosen tap (loaded tap) itself. This result is demonstrated in figure 10.

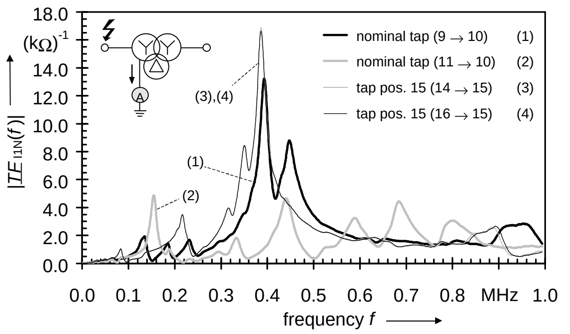

Figure 10: Effect of different applied taps and different directions for switching of the tap changer (TF of the neutral current; 200 MVA, 220/110/10 kV coupling transformer)

The effect of history becomes very obvious for nominal tap position. For non-nominal settings of the tap changer the non-loaded conductor of the tap selector is next to the loaded one. This small difference cannot be seen in the TF characteristics. Thus there is no practical restriction if the history is not further considered in any evaluation processes, except for nominal voltage transfer setting.

4. Conclusions

The effect of different handling for pre-trigger samples and different window functions is significant but in practice it disappears due to the uncertainty which is caused by the limited measuring accuracy.

Sensors and the grounding set-up strongly affect TF results. Thus, uncertainties must be considered if no information about the sensor transfer characteristics and the test set-up is known.

The applied tap is the most important effective condition parameter for TF results. For nominal tap position the direction of movement must also be known for TF evaluation.

5. References

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