CALCULATION OF THE TRANSFER FUNCTION OF A POWER TRANSFORMER WITH ONLINE MEASURING DATA

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Mechanical deformation in transformer windings can be detected with the transfer function (TF). Normally the transformer will be disconnected from the public power supply to record the TF (offline measuring). Another possibility is to calculate the TF from the transients overvoltages generated from switching operations or lightning strikes. With adequate sensors these overvoltages can be recorded during operation of the transformer (online-measuring). On the basis of these online-datas diverse problems like separation of excitation- and response signal, too low signal-to-noise ratio, etc. and their solution will be shown in this paper.

Key words - transformer, transient overvoltages, online measurement, transfer function (TF)

1 INTRODUCTION

The TF is a comparative method to monitor the mechanical condition of transformer windings. In principle there are two different ways to calculate the TF:

1. Directly in the Frequency Domain:
   The test object will be excited with a sinusoidal signal variable frequency. The respons is also a sinusoidal signal with the same input frequency, but with another amplitude level and a phase shift. The complex TF results from the quotient between out- and input signal.

2. In the Time Domain:
   The test object will be excited with a broadband pulse signal. The response signal results according to the impulse response. The complex TF results from the quotient between the Fourier transformed out- and input signal.

Normaly the transformer must be disconnected from the puplic power supply and the electric line must be unmounted for the TF measurements (offline measurements). But for the time domain measurements there is also another possibility: namly using transient overvoltages produced by switching operations or lightning strikes. These overvoltages spreads out over the public power supply and come in to the transformer. These transient events can be recorded during the operation and used for the calculation of the TF [1].

2 THEORETICAL BACKGROUND

2.1 THE TRANSFORMER AS A TWO PORT

Concerning the external connection, the transformer can be considered as a passive, time-invariant, complex and linear network. The linearity is based on the fact, that the most kinds of lamination do not have a noteworthy magnetisation for frequencies higher than 1 kHz [2], [3]. For that reason the form of the time-signals are not decisive, but the form of the spectra [4].

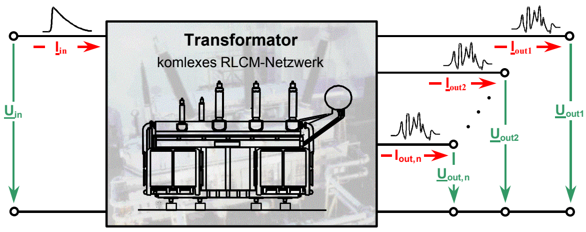

Figure 1: The transformer as a two port

The excitation of the transformer results with a transient signal. In principle all measurable electrical parameters on the transformer terminal are suitable for the response signal. According figure 1 for each response signal one TF can be define:

TF of input current:

$$\underline{TF}_{in}(f) = \frac{FFT(\underline{I}_{in}(t))}{FFT(\underline{U}_{in}(t))} = \frac{\underline{I}_{in}(f)}{\underline{U}_{in}(f)} \tag{1}$$

TF of ouput currents:

$$\underline{TF}_{out,I,n}(f) = \frac{FFT(\underline{I}_{out,n}(t))}{FFT(\underline{U}_{in}(t))} = \frac{\underline{I}_{out,n}(f)}{\underline{U}_{in}(f)} \tag{2}$$

TF of output voltages:

$$\underline{TF}_{out,U,n}(f) = \frac{FFT(\underline{U}_{out,n}(t))}{FFT(\underline{U}_{in}(t))} = \frac{\underline{U}_{out,n}(f)}{\underline{U}_{in}(f)} \tag{3}$$

2.2 ACCURACY OF THE MEASUREMENTS

The measurement signal is set out a serial of disturbing signals. Even at ideal measuring condition the quantization noise affect the measurement signal, because of the limited number of the amplitude steps. The effect is, that measurement signals are faulty and the following assessment is valid:

$$\{|\underline{X}(w)| - |\underline{X}_S(w)|\} < |\underline{X}_N(w)| < \{|\underline{X}(w)| + |\underline{X}_S(w)|\} \quad (4)$$

$$\{|\underline{Y}(w)| - |\underline{Y}_S(w)|\} < |\underline{Y}_N(w)| < \{|\underline{Y}(w)| + |\underline{Y}_S(w)|\} \quad (5)$$

Thereby are $|\underline{X}(w)|$ and $|\underline{Y}(w)|$ the magnitude of the measurement signals, $|\underline{X}_S(w)|$ and $|\underline{Y}_S(w)|$ are the noise level and $|\underline{X}_N(w)|$ and $|\underline{Y}_N(w)|$ are the wanted signal of the in- and output signal. Further it is visible that the wanted signal is between a band. The limits of this tolerance band can be calculated as follows:

$$|\underline{TF}(w)|_{\max} = \frac{|\underline{Y}_N(w)|_{\max}}{|\underline{X}_N(w)|_{\min}} = \frac{|\underline{Y}(w)| + |\underline{Y}_S(w)|}{|\underline{X}(w)| - |\underline{X}_S(w)|} \quad (6)$$

$$|\underline{TF}(w)|_{\min} = \frac{|\underline{Y}_N(w)|_{\min}}{|\underline{X}_N(w)|_{\max}} = \frac{|\underline{Y}(w)| - |\underline{Y}_S(w)|}{|\underline{X}(w)| + |\underline{X}_S(w)|} \quad (7)$$

3 REALISATION OF A ONLINE MEASURING SYSTEM

3.1 THE SENSORS

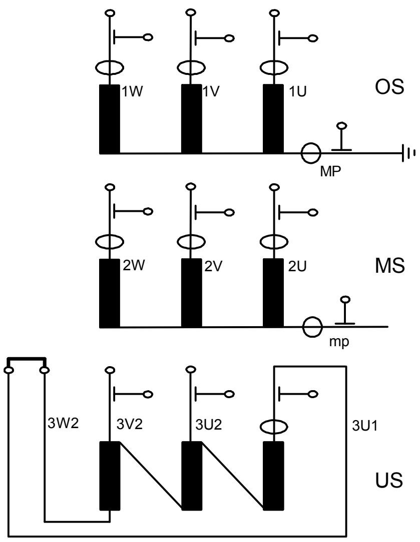

Figure 2: Block diagram of the 350-MVA-transformer
⊢O ≙ Voltage sensor
⊕ ≙ Current sensor

Many sensors are installed on a 350-MVA-system-interconnecting-transformer to record the transient travelling waves and the response signal. Figure 2 shows the location of the different sensors in the block diagram of the 350-MVA-transformer.

The voltage is measured with a special voltage sensor. These are mounted at bushings of the transformer near the dome. Combined with the bushing capacitance (see figure 3), the sensor constitute a capacitive divider. Provided that $C_S << C_A$, the transmission ratio can be mentioned with $n \approx C_A / C_D$.

The current sensor is a Rogowski-coil and is located in the bushing dome (see figure 3). To avoid non-linear effects the winding carrier exists from plywood. Additional the sensor is protected against electromagnetic interference with a longitudinal slotted copper-sheet-clad.

Because of the long way and to reduce the electromagnetic interference, the signals are transmitted with ~ 100 V from the sensors to the digital measuring system. Thus a level adaptation in two steps is necessary: 1.) direktly at the sensors for the transmission 2.) outside the measuring system for the input range of the transient recorder. A low pass filter is also integrated in the second divider to eliminate the aliassing effect.

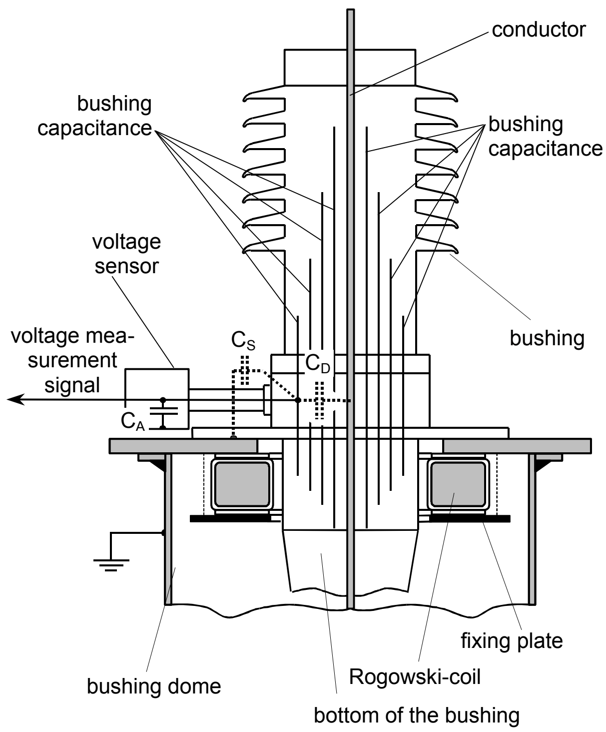

Figure 3. installed sensor technology

3.2 THE TRANSIENT SIGNALS

For an offline frequency response analysis (FRA) in time domain an one-shot low voltage impuls will be used for the excitation of the transformer. This impuls will be admitted defined to one transformer conducter. Therefore there is no coupling outside possible beween the conducters and a clearly separation of in- and output signal is given. Online measured transient signals are significant different as these of an impuls generator. Line couplings, reflections, relighting of arcs, etc. produce a series of oscillating part-events. As a result of this all part-events (peaks) of one phase can not be the excitation. Because of the need of a pure exciting signal it is not possible to use the full length of the recorded signal. Consequently only the single peaks can be used for the calculation of the TF. Any peak of any phase is clearly to see in the neutral point current, so it is suited for the peak dedection. The current will be searched for absolute values, which are higher than an adjustable trigger level. If the algorithmus found such values than it cuts out the belonging peak with an adequate length time in consideration of a pre trigger time.

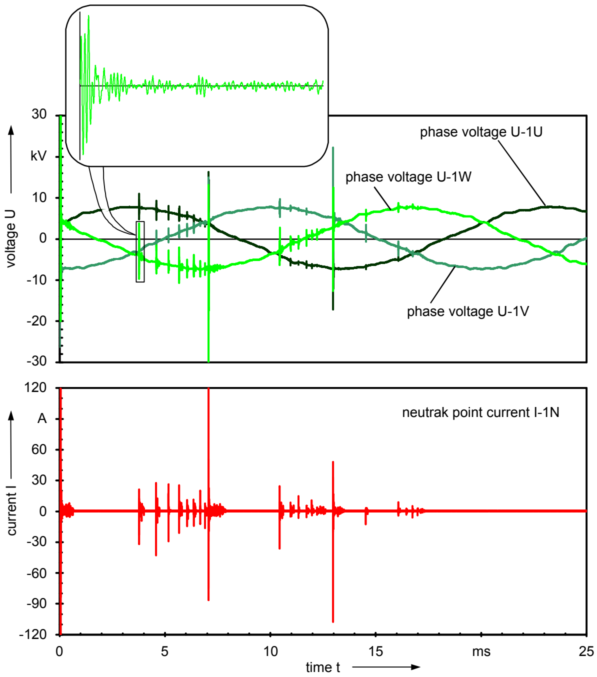

Figure 4: Recorded transient event with zoomed peak. 50 Hz component stronger attenuated as the peaks because of the transfer characteristics of the sensors

As a big problem, it was already mentioned, proves the classification of the peaks regarding cause and effect. However a first restriction can be done: the excitations signals are voltages. With the following presented algorithm should it be possible to do a classification of the peaks.

Normally the excitation signal has the steepest rising edge and therewith the highest cutoff frequency. The energy of the incoming impuls spreads out to the other terminals. In consideration of the transfer behavior and the resonances, the interfering puls should have the highest input voltage. A higher input voltage affects with a higher spectrum level. This are two criterias which are regarded by the calculation of the area til the highest cutoff frequency of all viewed channels. The signal with the greatest area is the input signal. Figure 7 clarifies the above explained issue. Problems with the algorithm are maybe possible by floating terminals. In this case the voltage distribution are mainly definite by the winding geometry. Thence it is possible that the picked up voltage on the floating terminals are very analogue to the excitation signal regarding curve characteristic and amplitude level. Concerning the basic circuit (star-, delta- or zigzag-connection) an open delta connection tends rather to this behaviour than an open star connection. If the terminals are grounded or the transformer are in operation the electromagnetic field will be distorted and a new voltage distribution will be adjusted along the winding. It has pointed out that in such set-ups the findings of the algorithm are dependable.

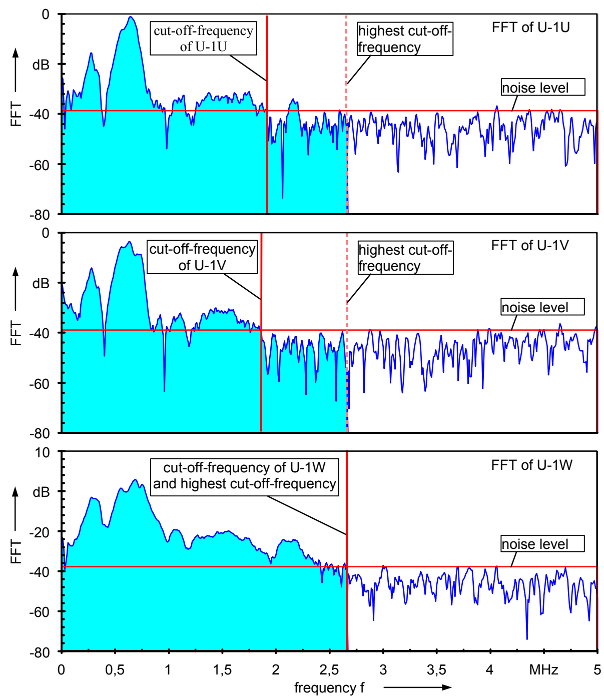

Figure 5: Calculation of the excitation signal

Analysis of the signal propagation delay is another possibility to find out the excitation signal. But the sampling rate of the transient recorder (100 ns) is as high as the signal propagation delay. Thus it can not be taken in consideration.

3.3 THE TRANSFER FUNCTION

The TF is a comparison diagnostic method, i.e. an assessment of a current measurements results from the comparison with an older measurement. If the insulation- and winding-conditions did not change the curve characteristic should also not change. To get a high reproducibility, the basic condition must be the same of the measured transient travelling waves [5].

The influencing factors are to search in the signal processing, condition parameters of the transformer and the configuration of the power system near the transformer. Following they are separate listed:

<u>Signal Processing</u>

→ Pre-Trigger:
  Different length of pre-trigger affects a different attenuation of the TF

→ Choice of Window Function:
  Different window functions affect a different attenuation of the TF

<u>Condition parameters of the transformer</u>

→ Temperature:
  Different temperatures affects a different attenuation of the TF. The effect is only significant when the temperature difference is higher than 20 K

→ Tapping Position:
  The electric characteristics changes by different tapping position. On the nominal tap position the direction of actuating is important to know, because the position of the non-loaded tap of the tap selector are once at the beginning and once at the end of the fine-step winding (depending on direction of actuating).

<u>Configuration of the Power System</u>

→ Changes in the configuration of the power system near the transformer cause reflection and refractions. These can have effects on the time characteristics of the signals and are not identifiable.

To keep the influence of the signal processing small, the same transformation algorithm will be used. The condition parameter of the transformer will be recorded minute-by-minute and are considered at the TF-comparison. The time-based storage is necessary to take conclusion about the direction of actuating. The registration of the configuration of the power system is at present still a problem because of missing corresponding intrefaces.

Figure 6 shows the comparison of two TFs which are recorded on different days. There is clearly to see that with the same basic condition the TFs are nearly identical. The identifiable differences can be explaine with the inexactness of the measurement and interference, because the differences are in the overlap area of the tolerance bands.

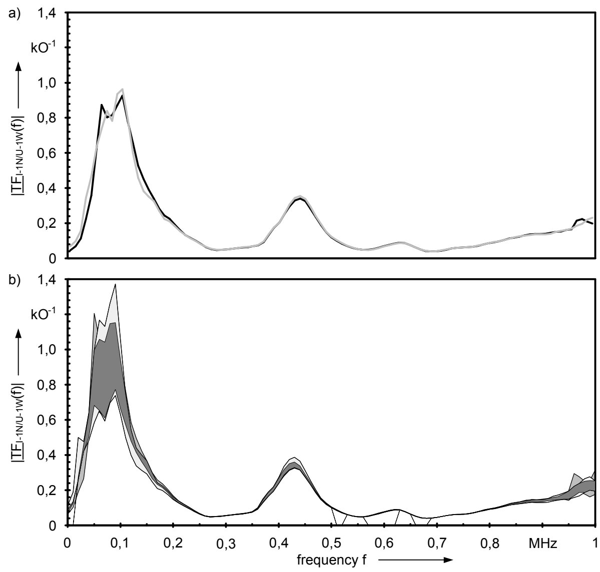

Figure 6: a) Comparison of two TFs, recorded on different days
b) Tolerance bands ot the TFs with the overlap area

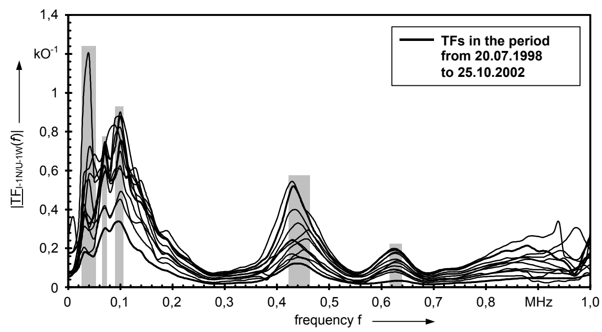

Figure 7: Comparison of several TFs. Recorded between 1998 and 2002 with the same tapping position

For using the TF as an effective monitoring method for insulation- and winding condition, a systematic monitoring must occur over a long period. If there are a significant difference between two calculated TFs it is an indication that something has changed on the electrical network of the transformer. Figure 7 shows the comparison of several TFs of the primary neutral point current, which are recorded between 1998 and 2002. As it can be seen in figure 7 there are visible differences between the TF curves. The characterisic curves show distincted attenuation, whereas the points of resonance nearly not shift. Only a change in attenuation is not a sufficient criteria for winding deformations. These occure mostly with resonance frequency shifting [4]. In this case the reason is to search in voltage-dependent resistor (varistor), which are installed parallel to the particular segment of the regulating winding. That causes a not linear system behavior. More reasons are:

- a not continuous spectra of the time signal
- different configuration of the power system
- change of divers parts of hardware (e.g. low pass filter) on the measuring system

3.4 FREQUENCY CONTENT OF THE TRANSIENT OVERVOTLAGES

A comparison between different TF is only possible till the smallest common upper limit of the frequency. Therefore for the calculation of the TF it is important that the bandwidth of the time signal is high enough. Areas in which dominates the noise are not meaningful because the domain of uncertainty gets too high. A statistic analysis of the transient overvoltages gives information about frequency content. Figure 8 shows the results of these analysis on the high voltage side phase.

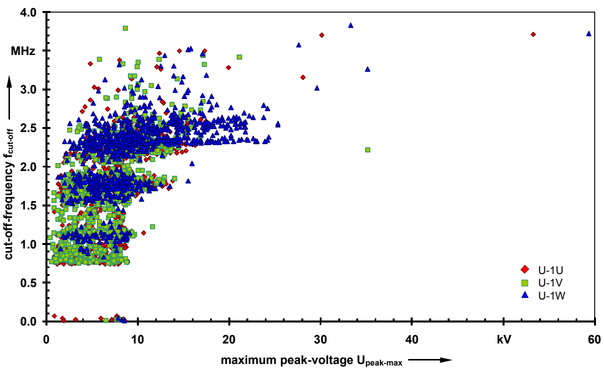

Figure 8: Frequency content of the transient overvotlages on the high voltage side phase

In this figure the cut-off-frequency of the signals are mapped over the maximum peak-voltage. There are three accumulation areas to see: first area about 1MHz, second area between 1.5 and 2 MHz and third area about 2.5 MHz. The peaks with the frequency content which are in first area must be viewed well, because in this consideration the cut-off-frequency is the frequency where the signal change to noise. Thus it is to assume that these peaks are not suitable for the TF contemplation. Average 19 trigger events occurs per month. As a result of this the recordings datasets can be abolish if the signal-to-noise-ratio or the cut-off-frequency are too low.

4 CONCLUSION

As opposed to the offline-measurements online-measurements allows a permanent monitoring of the insulation- and winding-condition. Another aspect of online-monitoring is, that exceeding voltages- and currents stress can be also monitored resp. registered. The first results shows that a online-analyses of the TF is possible. But it was also showed that some more influence factors like e.g. voltage-dependent resistor, different configuration of the power system, etc. and the compensation of it must be investigated.

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