Proceedings of the 2010 International Conference on Condition Monitoring and Diagnosis, September 6-11, 2010, Tokyo, Japan

Transformer Modelling Based On Frequency Response Measurements For Winding Failure Detection

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***Abstract*—Frequency response measurements are a widely applied technique for power transformer winding failure detection after lightning stroke, short circuit or transport and are more sensitive than the conventional short-circuit voltage measurements. Deviations between frequency responses indicate mechanical and/or electrical changes of the active part of a transformer. However comprehensive understanding about the resonance behaviour of frequency responses and the underlying electrical effects is missing. This paper describes how to derive an analytical electrically equivalent model from measured frequency responses. For the low frequency part containing few resonances, equivalent resonance circuits with physical meaning can be identified from measured data. For higher frequencies, an electrically equivalent circuit can be identified using an analytical expression gained by vector fitting.**

Keywords – Power Transformer, Transfer Function, Frequency Reponse Analysis, High Frequency Modeling, Vector Fitting, Transient, Resonance

I. Introduction

Besides other diagnostic methods, Frequency Response Analysis (FRA) can deliver useful additional information when assessing power transformers after short circuit event, lightning surge or transport. Mechanical irregularities of the active part such as deformations of windings as well as electrical changes like winding turn shorts can cause deviations in the frequency responses which are determined by winding impedances and mutual capacitive and inductive coupling of windings. The basic principle of FRA is the investigation of differences between frequency responses. Interpretation of differences between two transfer function (TF) curves is the missing link between failure identification, measurement and assessment of the transformer. So far, the diagnostic method is not standardized and lacks comprehensive modelling which on one hand reflects physical circumstances and on the other hand allows quantitative and more objective evaluation of transfer function differences. The goal of this paper is to establish a relationship between frequency response measurements, synthesis, i.e. approximation of analytical transfer functions on the basis of these measurements and deduction of basic electrical lumped elements circuit. Thinking out the idea of FRA together with analytical modelling offers the opportunity to create electrically equivalent circuits of power transformers that can contribute to predict and solve transient/resonance problems in power grids.

II. Transfer Function Measurement and Failure Types

The two most common used test types for transfer function measurement of power transformer are the so-called end-to-end transfer function $\underline{TF}_{EE}(f)$ measurement and the capacitive inter-winding measurement [1]. Fig. 1 shows the associated connection diagrams. The obtained transfer function of a measured winding then is:

$$\underline{\mathrm{TF}}_{\mathrm{EE}}(f) = \frac{\underline{U}_{2,EE}}{\underline{U}_1} = \frac{R \cdot \underline{I}_{out}}{\underline{Z}_{in} \cdot \underline{I}_{in}} \tag{1}$$

For the second measurement type, the transfer function is

$$\underline{\mathrm{TF}}_{\mathrm{CI}}(f) = \frac{\underline{U}_{2,CI}}{\underline{U}_1} = \frac{\underline{Z}_{2,in,open} \cdot \underline{I}_{2,in}}{\underline{Z}_{1,in,open} \cdot \underline{I}_{1,in}}. \tag{2}$$

For large transformers with greater stray capacitances to ground potential, input current $\underline{I}_{in}$ and output current $\underline{I}_{out}$ deviate.

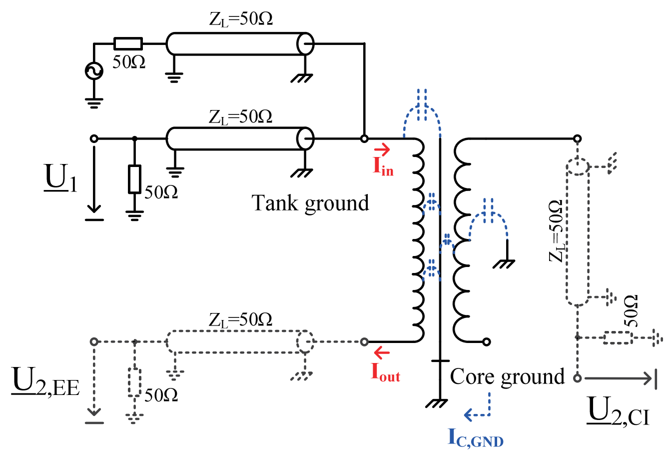

Figure 1. Connection schemes for measurements of end-to-end (EE) and capacitive inter-winding (CI) frequency response.

Differences become significant with higher frequencies since the impedance is more and more dominated by capacitances. As a result, the true input admittance of the winding cannot be calculated from the voltage ratio $\underline{TF}_{EE}$. For smaller transformers and in lower frequency range, stray capacitances to ground are negligible and the impedance of a winding $Z_w(f)$ can be approximated by solving the voltage divider ratio $\underline{TF}_{EE}(f) = \underline{U}_2/\underline{U}_1 = R/(R+\underline{Z}_w)$ for $\underline{Z}_w$:

$$\underline{Z}_w(f) \approx R \cdot \left(\underline{TF}_{EE}(f)^{-1} - 1\right) \qquad (3)$$

However, an accurate measurement of the input impedance is only possible when the input current is measured. The capacitive ground current $\underline{I}_{C,GND} = \underline{I}_{in} - \underline{I}_{out}$ is sensitive towards variation of the winding geometry hence it directly depends on the stray capacitance of the winding coil of high or low voltage side. The known deformation types buckling and spiralling result in changes of distances between winding and core or winding and tank. For this reason, the end-to-end TF is possibly susceptible to respond to these failure types. The capacitive inter-winding TF is most sensitive towards geometrical variations between windings, since the coupling between higher and lower voltage winding is almost purely capacitive. In case of a deformation, an increase of the transformer short circuit impedance means a change of the main stray flux path which also results in a variation of the capacitances between windings. In summary it can be said that different transfer function types have different sensitivity towards failure modes [1] which justifies several measurements for FRA.

III. Analytical Modelling of Transfer Functions

The analysis of power transformers' transfer function is based on the assumption that the electrical behaviour is linear over the frequency range of interest. Thus, any type of measured transformer TF can be described by a rational function

$$H(p) = \frac{\prod_{\mu=1}^{M}(p - z_\mu)}{\prod_{\nu=1}^{N}(p - p_\nu)} = a + Kp + \sum_{\nu=1}^{N} \frac{d_\nu}{(p - p_\nu)}, \qquad (4)$$

where z_μ are zeros, d_ν residues and p_ν complex poles of the known frequency response $\underline{TF}(f) = H(p \rightarrow j \cdot 2\pi f)$. The accuracy of this approximation mainly depends on its ordinal number N, i.e. $N/2$ conjugate complex pole pairs. To derive $H(p)$ from a measured frequency response, the proven vector fitting (VF) method [2] was adapted. Fig. 2 shows approximation and measured end-to-end transfer function of a three phase 200 MVA, 110 kV/65 kV transformer (phase V) using complemented vector fitting. The needed number of poles was firstly pre-estimated on the basis of resonance peaks of a moderately smoothed magnitude $|\underline{TF}(f)|$. Pre-positioning and iterative adjustment of the number of complex pole pairs leads to a fitting result with predefined accuracy [3]. The requirements concerning accuracy of the fitting result are determined by the achievable reproducibility of sweep frequency response measurements, which naturally degrades with higher frequencies [4], [5]. Accuracy is theoretically not limited by the algorithm, however the number of poles increases with higher accuracy. The method of pre-estimation of the needed number of pole pairs on the basis of resonances roughly delivers numbers between 30 and 100 pole pairs (depending on transformer type, frequency range, number of frequency samples) corresponding with visible number of resonance peaks. The resulting analytical transfer function then contains all physically relevant information of a measured frequency response. Additionally, the information density is increased, since the amount of data is reduced. Finally, in this form, a transfer function is independent of the number of frequency samples and can be compared to another frequency response with different number or distribution of frequency samples more easily.

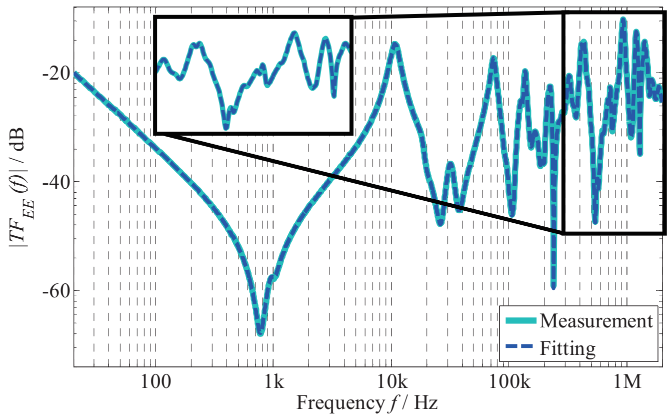

Figure 2. Approximation vs. measured data: End-to-end transfer function of 200MVA 110 kV/65 kV transformer.

IV. Low Frequency Transformer Model

Analysis of a variety of power transformers' end-to-end TF with different power and voltage ratings, vector group and number of phases reveals common features of the frequency responses [6]. Fig. 3 shows the end-to-end TFs of the above mentioned transformer (high voltage windings). Characteristic frequency bands can be identified in the frequency response of almost any tank type transformer (here marked with solid vertical lines). The frequency bands FB1 and FB2 are related to the core (up to few kHz). The frequency sub-bands FB3 and FB4, beginning with the second resonance up to several 100 kHz are determined by the interaction of windings and are therefore sensitive towards geometrical changes. Interpretation of deviating frequency responses needs understanding of the fundamental elements of a transformer and the composition of the transfer function by several factors. Often, failures yet appear as deviations in the kHz range of the frequency response [7]. In this case, deviations can be modelled within a simple lumped elements circuit derived directly from the magnitude TF curve.

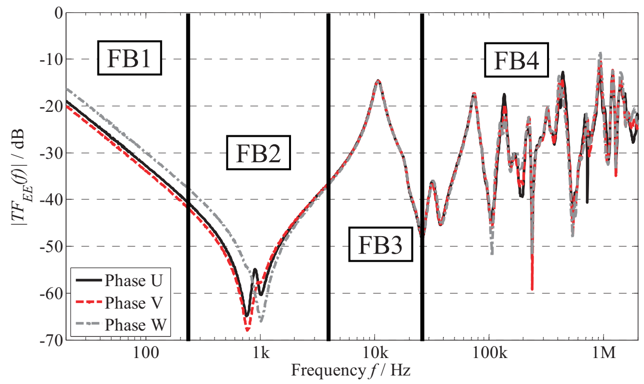

Figure 3. Characteristic frequency bands of end-to-end TF.

For this purpose, a SPICE simulation model was created. Fig. 4 shows the corresponding equivalent electrical circuits creating the first 3 resonances. The elements are:

- Copper resistance of windings R_{Cu}
- Leakage inductance of windings L_σ
- Magnetising inductance L_m
- Core loss resistance R_{Fe}
- Winding series capacitance C_s
- Capacitance of inter-winding coupling C_{iw}

For measureable frequencies from 20...100 Hz, the winding impedance behaves purely inductive. Using (3) gives

$$L_m \approx \frac{R}{j\omega} \cdot \left(\underline{TF}_{EE}(f)^{-1} - 1 \right) \Big|_{20\,\text{Hz} < f < 100\,\text{Hz}}, \tag{5}$$

assuming $L_m >> L_\sigma$. The first resonance is determined by the input capacitance between terminals in parallel to L_m. Hence

$$C_s = \frac{1}{(2\pi f_0) \cdot L_m}. \tag{6}$$

Of course, due to the nonlinear behaviour of the core (residual induction, frequency dependence) and superposition of other electrical elements these values may not be exact but rather estimated; they deliver an equivalent frequency response though. For second and third resonance frequencies (several 10 kHz), the core inductance is negligible since the magnetic flux is displaced inside the core by eddy currents. The resonance frequencies are determined by C_{iw} and L_σ of adjacent winding(s):

$$f_1 = \frac{1}{(2\pi) \cdot \sqrt{L_\sigma (C_s + C_{iw})}} \Leftrightarrow C_{iw} = \frac{1}{(2\pi f_1)^2 \cdot L_\sigma} - C_s \tag{7}$$

$$f_2 = \frac{1}{(2\pi) \cdot \sqrt{L_\sigma C_s}} \Leftrightarrow L_\sigma = \frac{1}{(2\pi f_2)^2 \cdot C_s} \tag{8}$$

Major changes of these parameters in the lower frequency range of 10 kHz ... 100 kHz indicate severe failures e.g. bulk movement of the winding. It is expected, that these failures can also be seen in a change of the short-circuit impedance though.

At present, the approach of identifying an equivalent lumped element circuit for the low frequency range is considered to be unperfected and will need more refinement; however it shows that it is possible to identify the meanings of low frequency resonances which are visible in the TF curve shape in order to interpret measurements with rough deviations.

V. Higher Frequency Transformer Model

For higher frequencies, the identification of detailed electrically lumped element circuits with meaningful relation to the winding design derived from measured frequency responses is not possible. On the one hand, detailed information about the active part (winding coil design, sequence of HV, MV and LV winding coils, screen electrodes etc.) of transformers is not available to users of FRA. On the other hand, capacitive and inductive coupling mechanisms get more and more complex with higher frequencies. Additionally, non-linear effects like skin effect or proximity effect become considerable. Consequently, interpretation of TF measurements based on detailed lumped element models would be only an option to manufacturers of transformers; however this is not a satisfying solution to FRA users.

As a result, an abstract transformer model without detailed knowledge about the inner assembly and design structure is needed. So far, assessment of deviating TF curves is neither standardised nor objective but is dependent on experience and subjective knowledge of users and experts. From the authors' point of view, assessment of frequency responses should comprise models which are not independent from physical meaning of the measurements. In the medium term, a hybrid model is favoured. The winding impedance (or admittance) then is virtually divided into two parts. The first part is representing the low frequency behaviour and consists of some basic lumped element circuits that build up the first few resonances [8]. Using additional knowledge about the topology of this circuit, some RLC values can in principle be derived from the measured TF magnitude curve as showed above. The second part consists of a electrical multipole model which is derived from the analytical transfer function created through vector fitting on the basis of measurements, see Fig. 5. The creation of the model on the basis of a measured TF is done by executing the following steps:

- Synthesis of the analytical representation by Vector Fitting
- Identification of low frequency (LF) part of the model

- Calculation of LF elements and separation of LF part from the analytical TF gained by VF

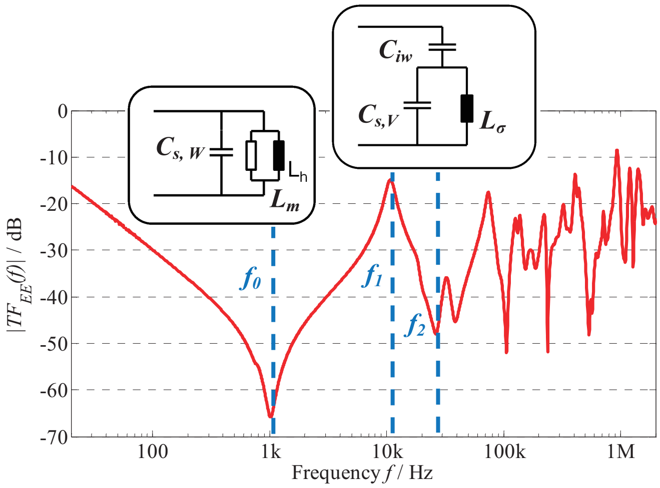

Figure 4. Equivalent resonance circuits for low frequency resonances involving coupling capacitances of adjacent windings.

The result is an electrically equivalent impedance model. The high frequency (HF) part can optionally be subdivided into single resonance circuits using partial fraction expansion.

The intention of the model is a more objective approach for interpretation of TF measurements. Advanced application is to provide equivalent models for prediction of interaction between transformers and ambient power grid, i.e. simulation of electrical transient responses.

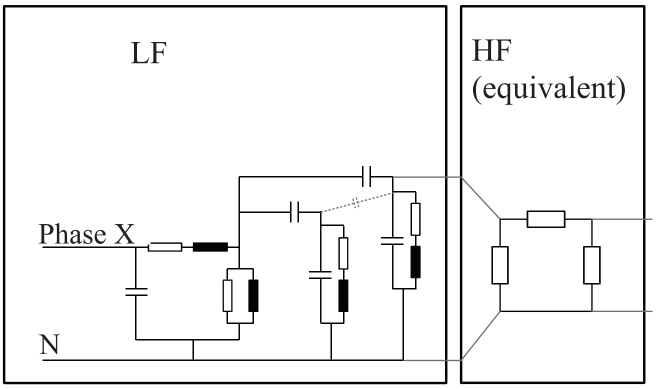

Figure 5. Single phase, hybrid electrical equivalent transformer model

VI. CONCLUSION

Although it is in practice for many years, the issue of interpretation with FRA is still not solved comprehensively. At the end of the day, an objective algorithm with physical basis is needed.

Although they show common response to geometrical changes of the transformer active part, different TF types have different sensitivity towards various failure types. However, there's no guideline recommending certain transfer function types for measurements. It was shown, that the impedance of single star-connected windings can be estimated from the end-to-end transfer function.

The vector fitting algorithm offers a suitable solution in order to find analytical expressions for measured transfer functions. Needed accuracy of the approximation can be controlled by the user according to the requirements of the application. The advantage of a mathematical description of TF over numerical data is that subsequent algorithms and assessment rules can be implemented more traceable, since identification of resonances out of numerical data often shows poor reproducibility.

In this paper it is suggested to derive an electrical equivalent model from measured TF. The model is subdivided into a low and a high frequency part. For the low frequency part containing few resonances, equivalent resonance circuits with physical meaning can be identified from measured TF. For higher frequencies, an electrically equivalent circuit can be identified using the analytical expression gained by vector fitting.

For the LF model, deviations between measurements can be interpreted as changes of the lumped element RLC values. For the HF model, deviations can be interpreted as changes of poles and zeros of the analytical TF.

Further, the model can be used to create precise electrical representations of transformers for transient simulations that help to predict harmful resonances between transformers and the circumjacent power grid.

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