Wind Turbine Transformer Impedance Identification Based on Time-domain Measurements

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***Abstract*—Frequency response analysis (FRA) based on a sinusoidal frequency sweep is a well-known method for impedance identification for transformers and other components. A new method for impedance identification for transformers based on time domain (TD) samples has been investigated and compared to classical FRA measurements. The major challenges are described: 1. accurate measuring techniques. 2: signal to noise ratio, (S/N). 3: linearity. 4: digital signal processing. A Matlab algorithm calculating the TD-based transformer impedance has been developed and verified by laboratory TD-measurements of a 3 phase star-delta coupled transformer as well as validated against FRA measurements. Finally the approved algorithm was applied to real wind turbine (WT) transformer samples provided by DONG Energy, which showed mixed results that are strongly connected to the S/N ratios.**

I. INTRODUCTION

Simulation studies for complex power grids are becoming more and more important these days. A precise frequency dependent impedance characteristic for transformers plays an important role in these simulations. Typically, the wind turbine transformer manufacturers do not provide frequency dependent impedance characteristics, but only specifications for the fundamental frequency (50Hz/60Hz). Transformer frequency dependent impedance characteristics could contribute to: 1. more precise damping estimation can potentially reduce the harmonic filter size and costs during wind farm design; 2. resonances and damping can be evaluated more precisely in harmonic emission and stability studies.

Classical FRA measurements require disconnection of the transformer before the analyzing process can be initiated. TD samples can be measured during normal operation, which is a great advantage over FRA measurements. E.g. live-monitoring systems could be developed that could reveal any changes in the impedance characteristic after a fault event. To improve and verify the Matlab algorithms, laboratory measurements were made on a small 200VA iron core transformer for single phase measurements and 3 identical 200VA transformers for 3-phase measurements. The transformer(s) were loaded by both purely resistive loads, inductive/capacitive loads and highly non-linear loads to discover if the results were disturbed by influences from the current draw.

This paper is based on the results of a Master of Science thesis in electrotechnology at the Danish Technical University in cooperation with DONG Energy during the spring of 2014.

II. T-MODEL OF TRANSFORMER

To be able to calculate both the excitation impedance and the branch impedances of a transformer by TD samples of the terminal voltages and currents only, the classical T-model for the transformer shown in Figure 1 was used [1]. This model is only valid for the low frequency impedance characteristic before the parasitic capacitances affect the impedance response (<10kHz). Equations for the excitation/magnetic impedance (R_m, L_m) and the branch impedances (L_p, R_p *and* R_s',L_s') have been derived from the terminal voltages (V_p,V_s) and currents (I_p, I_s) of a single phase transformer.

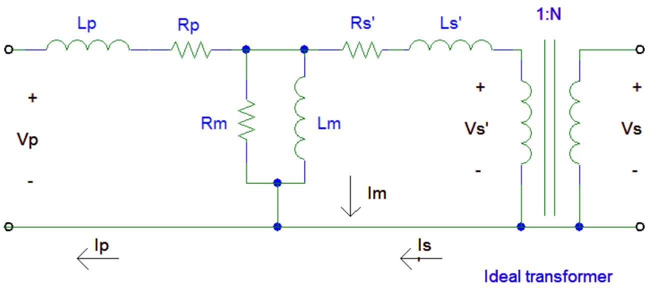

Figure 1. T-model of a transformer.

$$Z_m = \frac{V_p I_s' + V_s' I_p}{I_p^2 - I_s'^2} \quad (1)$$

$$Z_b = \frac{V_p}{I_p} - \left(\frac{V_p I_s' + V_s' I_p}{I_p^2 + I_s' I_p} \right) \quad (2)$$

III. MATLAB ALGORITHMS

The Matlab algorithms load the recorded voltage and current samples and scale them to real values before they are processed by bandpass filters for each harmonic including the fundamental. (e.g. 50Hz, 100Hz, 150 Hz, etc.). Butterworth bandpass filters are used with a flat response around the center frequency to assure immunity to changes in the fundamental frequency. Each bandpass filtered signal is analyzed to extract the magnitudes and phase relations of the signals to give a complex number representation. The complex numbers are then inserted into equation (1) and (2) to calculate the impedance values for the current harmonic. A list of impedance values is then exported as a file, ready to be imported by other software tools like PowerFactory, etc.

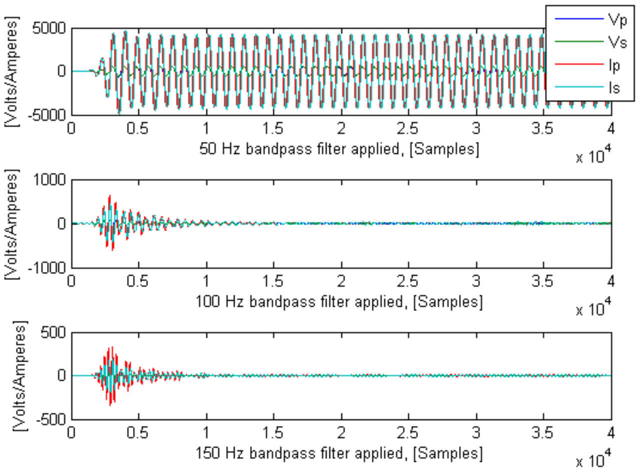

Figure 2. WT transformer data bandpass filtered.

The transient response of the bandpass filters is very dominant compared to the steady state period afterwards, as shown in figure 2. It's therefore important to cut off the transient period before estimating the magnitude and phase relations. Even after the steady state has been reached, the magnitude and phase are not entirely stable, which make the calculation of the phase relation inaccurate. Therefore, several hundred phase relation calculations are made throughout the steady state period. An average value can then be calculated to give more accurate phase angles.

IV. TIME DOMAIN MEASUREMENTS

A 50=Hz triangular voltage source were connected to the primary terminals of the transformer/test-object to insure a high number of upper harmonics for the recordings. Isolated battery powered voltage probes and isolated current probes were used to feed the voltage and current measurements to the data acquisition device; a 4 channel, audio interface with 24 bit resolution connected to a PC by firewire. A sample frequency of 96kHz was used, which gives a discrete phase angle accuracy of 7.5 degrees per sample for a bandwidth of 2kHz:

$$n_{5kHz} = \frac{96000\,\frac{samples}{s}}{2kHz} = 48\,\frac{samples}{period}$$

$$\sim \frac{360°}{48\ samples} \sim 7.5\ deg/sample \qquad (3)$$

Equation (3) shows that the discrete phase angle accuracy at 2kHz is acceptable without any further interpolation techniques applied [2]. For the measurements made in this project, the sampling frequency of 96kHz should be adequate for a bandwidth of interest of about 2kHz, which covers the most relevant harmonics in low frequency studies for power grids. Furthermore, "no-signal" noise recordings were made and processed for accurate S/N ratio calculations for each harmonic frequency. This was done by turning down the frequency of the tone generator to less than 0.1Hz to keep the noise contribution from the tone generator itself.

V. RESULTS

The results for the TD based impedance characteristics were compared with classical FRA measurements for verification. Generally, the TD results were fairly accurate as long as the S/N ratios for the recorded signals were greater than ~40dB.

A. *Single phase laboratory transformer*

Results for both excitation impedance- and branch impedance characteristics were made by using equation (1) and (2), and a "no-load" recording setup as another approach to obtain the excitation impedance. Even though the S/N ratio for the "no-load recording" was improved to be greater than 45dB by raising the voltage level, the impedance characteristics were still very inaccurate. This must be due to the non-linear behavior of the iron core, which introduce distortion components to the recorded signals. FRA measurements based on sinusoidal sweeps also showed different impedance characteristics for different voltage levels, which indicate non-linearity.

However, the branch impedance based on leakage inductance with air as the more linear magnetic material showed fine results, see Figure 3, Figure 4 and Figure 5.

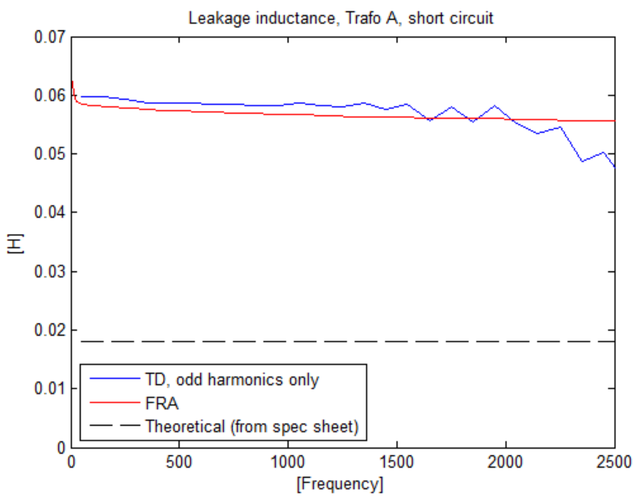

Figure 3. Branch inductance, 200VA laboratory transformer.

The theoretical values shown in the graphs are based on the transformer's "maximum rating" – specifications, which are not very reliable as reference for the TD based results. Focus should be kept on the comparison between TD and FRA characteristics, which showed fairly accurate results until 1.2kHz – 1.5kHz, where the S/N ratio approaches 40 dB as shown in Figure 5. The connection between S/N ratio and accuracy of the calculated impedance is therefore very important, which is illustrated by comparing Figure 4 and Figure 5.

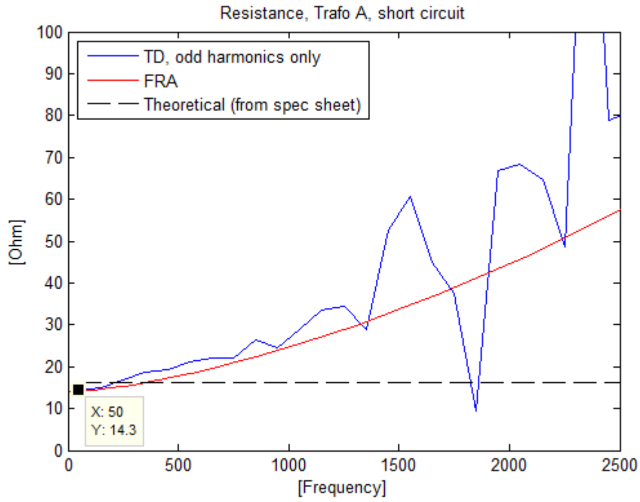

Figure 4. Branch resistance, 200VA laboratory transformer.

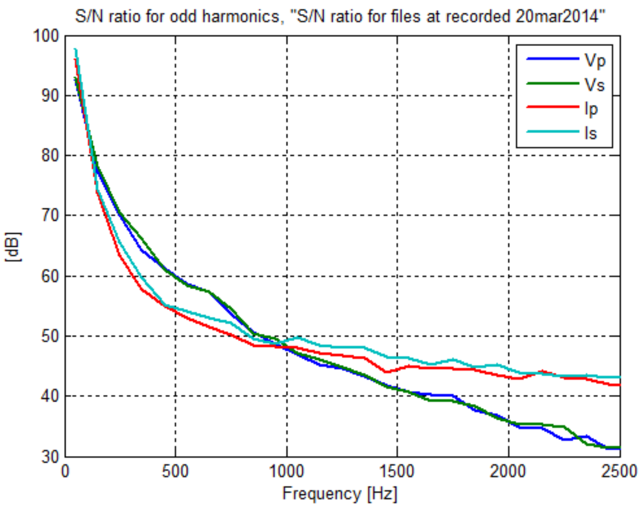

Figure 5. S/N ratio, branch impedance, 200VA laboratory transformer.

B. 3- phase, star-delta coupled transformers. (3×200VA)

Due to the typical star-delta coupling of wind turbine transformers, the laboratory tests of the 3 phase transformer were connected like this. The worst case load scenario of non-linear, non-symmetrical loads led to fairly accurate results as shown in figure 6 compared to the more precise results shown in Figure 3 and Figure 4. Note that the OMICRON three phase voltage generator's maximum upper harmonic for the triangular output used for the measurements was 950Hz. Here, the excitation current have been neglected because the secondary winding current is unknown due to the star-delta coupling. The result in figure 6 shows a rising resistance with the frequency due to the skin-effect similar to the resistance graph in figure 4. The inductance is fairly accurate even though it does not decline with the frequency as the result in figure 3. These results proof that branch impedance characteristics based on TD recordings are possible even for 3 phase star-delta coupled transformers loaded by non-linear, non-symmetrical loads.

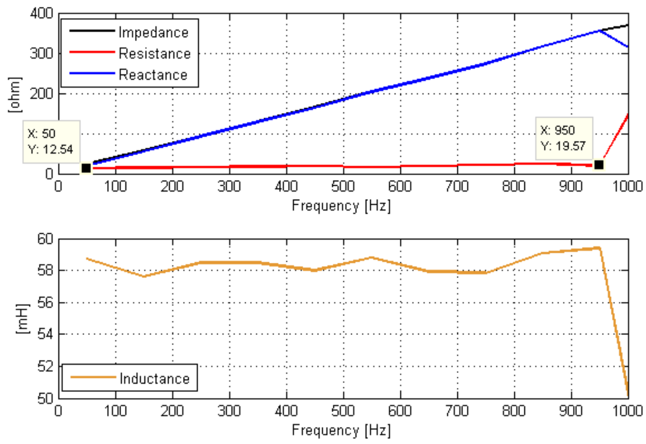

Figure 6. Branch impedance, 3 phase star-delta coupled transformer loaded by non-linear, non-symmetricl loads.

C. WT transformer data from DONG Energy

I. Arana and Ł. Kocewiak recorded some samples of a WT transformer in the nacelle of an off shore WT. [3], [4]. These data have been processed by the Matlab algorithm verified by the laboratory results. First, an FFT plot of the data was plotted to observe the S/N ratio, see figure 7 below.

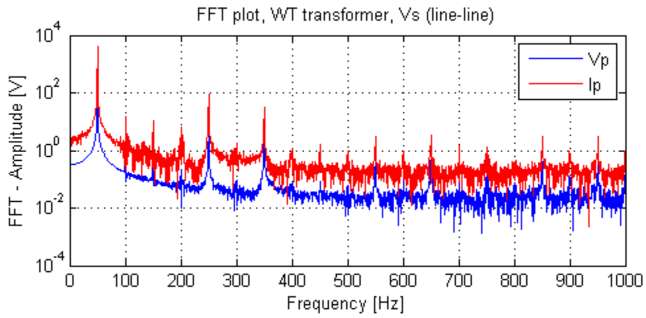

Figure 7. FFT plot, wind turbine transformer, DONG Energy.

Here, only the fundamental frequency and the 5th harmonic (250Hz) have S/N ratios of minimum 40dB, (×100). A corresponding FFT plot from the laboratory measurements is shown in Figure 8 for comparison. Here, the S/N ratio is above 40dB for all upper harmonics within the 1kHz bandwidth shown.

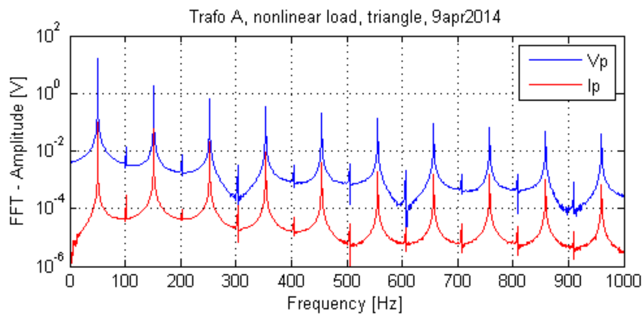

Figure 8. FFT plot, laboratory transformer measurments.

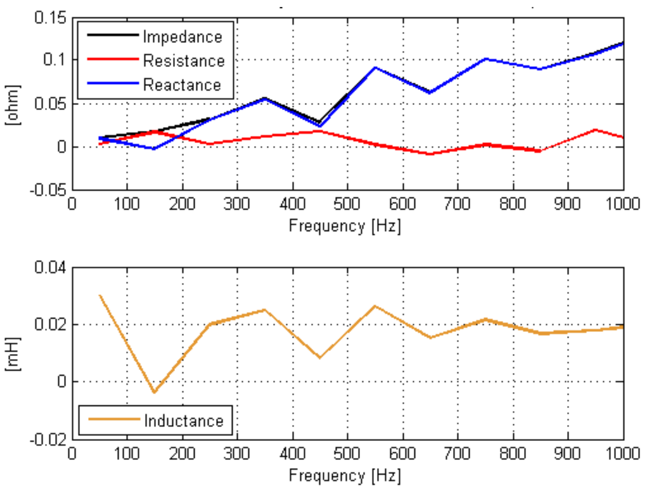

Figure 9. Branch impedance, WT transformer

Due to the poor S/N ratio shown in Figure 7, the impedance characteristic shown in Figure 9 and Table 1, only shows a seemingly accurate resistance value of for the 250Hz harmonic compared to the fundamental harmonic. Even though the inductance graph was not very accurate, it averages around 20µH, which is close to the value based on the manufacturers specifications of 23.2µH. Just as for the laboratory measurements, the results for the WT transformer also indicates the necessity of acceptable S/N ratios. (>40dB).

TABLE I.

Z_b	**WT transformer, branch impedance characteristic**		
	Manufacturers specifications	***50Hz (TD)***	***250Hz (TD)***
Resistance	1.03 mΩ	2.5 mΩ	2.7 mΩ
Inductance	23.2 µH	30 µH	20 µH

VI. Conclusion

Matlab algorithms have been developed that are able to calculate the branch impedance characteristic for a transformer in the low frequency range based on time domain recordings. The algorithms have been verified against FRA measurements and approved for worst case scenarios for both single phase and three phase transformers. (Non-linear, non-symmetrical loads.) The major challenges/requirements have been described:

1. S/N ratio should be greater than ~40dB for all upper harmonics of interest to assure accuracy.

2. The voltage-current characteristic of the measured device has to be linear.

3. High phase angle accuracy of the recorded signals is important. This can be obtained by choosing a high sampling frequency (96kHz sampling rate results in 7.5 degrees/sample @ 2kHz) or by implementing accurate interpolation techniques. A high bit resolution of 16 – 24 bit is required as well to assure overall S/N ratio.

4. For three phase star-delta coupled transformers, the branch impedances can be identified by the terminal voltages and currents by neglecting the excitation current. Here, the branch currents should be much larger than the excitation current.

Finally, TD samples for real WT transformers from DONG Energy have been processed by the verified Matlab algorithm with mixed results. Only the 250Hz harmonic had a S/N ratio of about 40dB, which led to a seemingly accurate result in contrast to all other harmonics. This indicates the necessity of a S/N ratio greater than ~40dB.

VII. Future Work

The main challenge of obtaining TD impedance characteristics is to record signals with acceptable S/N ratios. Battery powered, galvanic isolated probes and double shielding techniques could be implemented for future measurements. Also appropriately secured low impedance common grounding point would possibly minimize current loops. Additionally high impedance data acquisition inputs could reduce the loading error.

Live monitoring systems could be made based on TD-recordings, which could be used to identify aging of transformers and the condition after i.e. a short circuit event.

The electromagnetic environment inside the nacelle of a WT is very challenging, when noiseless recordings have to be made [5]. Long test cables are hard to avoid due to the large physical dimensions of the transformer, switchgear, etc. Locally placed battery operated preamplifiers in well-shielded cabinets might be a way to improve S/N ratios. From the preamplifiers, the signals could be transmitted via well-shielded balanced cables to the A/D converter unit, which could be placed away from the most critical electromagnetic environment.

Naturally, the level of upper harmonics in the low frequency band in well-designed power systems are still quite low making it challenging to obtain good S/N ratios. Searching for events or heavy non-linearities in the power system that give rise to increased harmonics could lead to recordings with improved S/N ratio of the upper harmonics.

References

[1] J.D.Glover, M.S.Sarma, T.J.Overbye, ”Power System Analysis & Design,” Fifth edition, 2012

[2] P.Denbigh, “System Analysis & Signal Processing,” 1998.

[3] I.A.Aristi, “Switching overvoltages in offshore wind power grids,” Ph.D., Danish Technical University, 2011.

[4] L.H.Kocewiak, “Harmonics in large offshore wind power grids,” Ph.D, Danish Technical University, 2012.

[5] L.H.Kocewiak, I.A.Aristi, J. Hjerrild, T. Sørensen, C.L. Bak, J. Holbøll, “EMC of harmonic and transient measurement equipment in offshore windfarms,” DONG Energy, Trondheim, Norway, 2012.