Wide band characterization of wind turbine reactors

A. Holdyk, I. Arana, J. Holboell

***Abstract*— This paper presents the results of field measurements of the impedance of two commercial available wind turbine reactors, performed by a sweep frequency response analyzer, sFRA. The measurements were taken in the frequency range from 20 Hz to 20 MHz. Comparable frequency behavior was found in all performed measurements with significant resonances at 1MHz for the 4.5 MVAr wind turbine reactor and 2 MHz for the 2.6 MVAr wind turbine reactor. Quadratic approximation was found to be suitable for the normalized resistance variation of the 2.6 MVAr wind turbine reactor in frequencies from 20 Hz to 10 kHz. At frequencies below 1 kHz, the normalized resistance was nearly identical for both reactors.**

Additionally, the accuracy of the measurement instrument was validated by comparing measurement results from two simple systems, comprising of a coil (L-system) and a series combination of coils and resistors (RL-system) with the results obtained from two high precision instruments. High accuracy of the sFRA instrument was confirmed.

***Keywords*: wide band models, sFRA, reactors, wind turbines, frequency domain measurements.**

I. Introduction

REACTORS are widely used in power systems for reactive power compensation, and often in wind turbines with full rating converters. In harmonic or transient studies, accurate representation of reactor models in the relevant frequency range is essential. For many purposes, it is satisfactory to model reactors as lump inductors in series with a resistor; however, for high frequency and transient studies, the stray capacitances should also be taken into account, including both capacitances from winding to ground and between the terminals. Moreover, a realistic representation of the damping at higher frequencies should be included [1]. Those detailed parameters are often difficult to obtain from the manufacturers. If only a linear model of a reactor is needed, as a reasonable approximation with no saturation effects included, it is possible to measure the parameters and represent the component in transient simulation programs as an n-port, in the simplest case a 2-port. The representation is often done in a form of a voltage and current relationship:

$$I(s) = Y(s) \cdot U(s) \qquad (1)$$

where I and U are current and voltage vectors at the terminals and Y is the admittance matrix, the size of which depends on the number of terminals. All parameters, voltages, currents and admittances are expressed in frequency domain and can be measured directly, e.g. by using sweep frequency analysis (sFRA). The outcome of such measurements can be used to find the resistance and inductance parameters for lumped representation of an inductor at varying frequencies.

sFRA is a measurement method where a sinusoidal voltage of varying frequency is applied to a device under test (DUT) and where the measured quantity is usually another voltage, giving a transfer function, but might also be current, hereby obtaining admittance. Some sFRA-based test systems have mainly been developed for transformer diagnostic and modeling purposes, but the equipment can also be used to measure other power system components, such as inductors.

This purpose of this paper is to qualify the use of a FRAX-101 sFRA instrument for field tests and to present results from sweep frequency response analysis (sFRA) measurements performed on two wind turbine reactors within a wide band of frequencies. Four systems are investigated during validation of the measurement instrument:

- a single coil (L-system)
- a series connection of an inductance (a coil) and a resistance (RL-system)
- a 2.6 MVAr wind turbine current limiting reactor
- a 4.5 MVAr wind turbine current limiting reactor

Measurements of resistance and inductance of simple L and RL systems are made by three different measurement systems and compared allowing validation of the measurement setups. Based on the results, one measurement system is chosen to measure 2.6 and 4.5 MVAr wind turbine reactors.

The following section describes the used measurement systems, measurement setups and DUTs. Section III shows the results of measurements performed on simple R and RL-systems and section IV gives the results for wind turbine reactors. The uncertainties of the measurement results are discussed in section V.

II. Measurement setups and equipment

Simple R and L components were chosen and measured by three different measurement instruments in order to validate sFRA measurement systems and methods. The L and RL systems were measured with a Frax-101, an Omicron cmc 256plus [2] and an HP 4149A analyser [3]. The two wind turbine reactors were measured by means of the Frax-101.

Megger's FRAX-101 [4] is a sweep frequency response analyzer with two analog inputs (AI) and one analog output (AO) generating sinusoidal voltages of up to 10V and frequencies from 20Hz to 25MHz. It is mainly used for transformer diagnostics [5] but has been also successfully used for performing short circuit admittance measurements for

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black-box models of power transformers [6].

The Omicron cmc 256plus is a high precision relay test set and universal calibrator. It is based on six current outputs 6x12.5A with variable frequencies from 10Hz to 3kHz. The device is not able to automatically vary the frequency, i.e. to perform frequency sweep, which needs to be done manually.

The HP4149A is a high accuracy impedance/phase-gain analyser with variable frequencies from 10Hz to 40MHz.

The measurements and simulations performed on both systems are shown in Table 1.

TABLE 1: MEASUREMENTS AND SIMULATIONS PERFORMED

	L-system	RL-system	2.6 MVAr and 4.5 MVAr
Components	Simple inductor: L = 0.5mH	Two parallel resistors and three parallel coils connected in series. Each inductor: L = 0.5mH; Each resistor R = 1 Ω	Wind turbine reactor
Location	Laboratory	Laboratory	Wind Turbine manufacturer's factory
Frequency range for comparison	20Hz to 40MHz	20Hz to 1kHz	20Hz to 10MHz
Megger FRAX-101	X	X	X
Omicron cmc 256plus		X	
HP 4149A	X		

The main idea behind these tests is to compare the results from the FRAX-101 against other measurement equipment at high and low frequency. At high frequency - against the HP4149A and at low frequency - against the Omicron cmc 256plus.

III. MEASUREMENTS OF L- AND RL-SYSTEMS

The inductor measured in the laboratory is shown in Fig. 1.

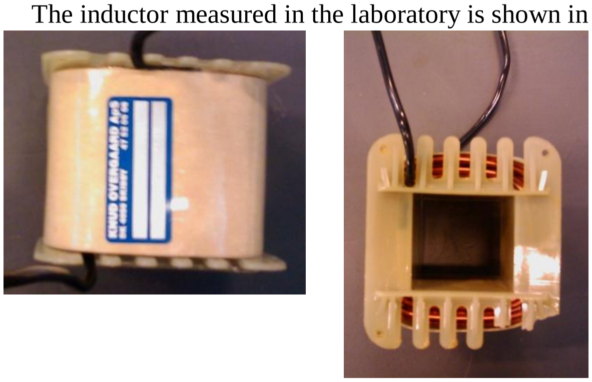

Fig. 1. Inductor used to create the L-system.

Fig. 2 shows the connection of the inductor to the measurement equipment HP 4149A.

Fig. 2. L-system connection during frequency domain measurements with HP 4149A

The RL-system measured in the laboratory is shown in Fig. 3.

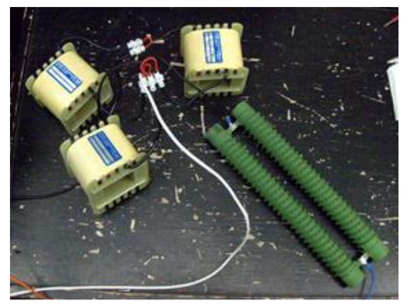

Fig. 3. Physical components used to create the RL-system.

The results from the measurement of the L-system are shown in Fig. 4 and Fig. 5, while the results from the measurements of the RL-system are shown in Fig. 6 and Fig. 7.

Fig. 4. L system measurement results with HP 4149A

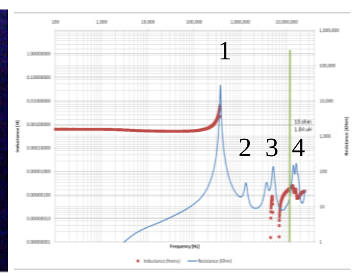

Fig. 5. L system measurement results with FRAX-101. The resonance peaks are numbered.

Fig. 4 shows inductance - yellow trace, and resistance – blue trace, measured by the HP 4149A. Fig. 5 shows the same quantities measured by Frax-101. Trace blue depicts resistance while red trace depicts inductance. Both figures were placed next to each other for comparison, as only screenshot was available from HP 4149A. The resonances were indicated at both figures by numbers 1 to 4. The first resonance appears before 400 kHz, followed by the second, third and fourth resonances in both measurements. The equivalent resistance is the real part of the measured impedance and the equivalent inductance is the imaginary part of the impedance divided by 2πf. At around 3kHz in both measurements, the equivalent resistance reaches the lower limit of the graph. After 5 MHz some differences appear between measurements, even more clearly visible between the third and fourth resonance, where the equivalent inductance from the FRAX-101 measurements presents a higher magnitude. The equivalent resistance measured by FRAX-101 matches very well the resistance measured by HP 4149A, until its frequency limit of 25 MHz.

The low frequency measurement results present slight deviation regarding the datasheet equivalent resistance (Fig. 6) and inductance (Fig. 7). The measurement results using the FRAX-101 and Omicron cmc 256plus present higher resistance and inductance than the equivalent datasheet values.

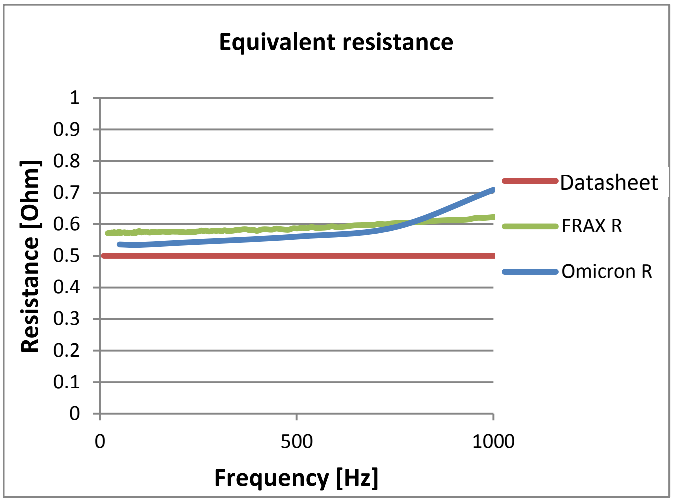

Fig. 6. Measured frequency dependence of the equivalent resistance of RL system.

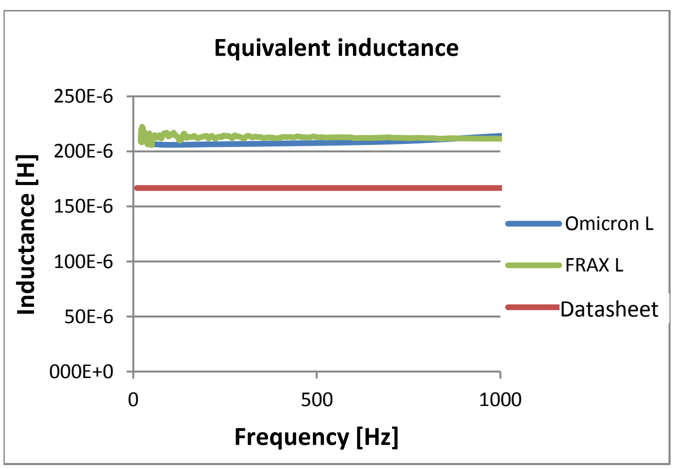

Fig. 7. Measured frequency dependence of the equivalent inductance of RL system.

The increased resistance might be due to contact resistance or due to mismatch between true and nameplate parameters. The measurement with the cmc 256plus was done using a dedicated fixture for high precision impedance measurements, which can explain better agreement to theoretical values at low frequencies.

The equivalent resistance from the FRAX-101 and Omicron cmc 256plus are very close to each other until 800Hz, when the measured values from Omicron seem to increase more than the FRAX results. On the other hand, the equivalent inductances from the FRAX and Omicron are very close to each other for the entire frequency range measured.

IV. Measurements of Wind Turbine Reactors

The previous section showed sufficient accuracy of Frax101 in measurements of both resistance and inductance of simple components. Additionally, the instrument is relatively simple to use, small and light and therefore suitable for on-site measurements, as here in the case of two wind turbine reactors in the wind turbine manufacturer's factory.

The name plate data of the 2.6 MVAr and 4.5 MVAr reactor is shown in Table II. The reactors were made by different manufacturers and no details about their construction are known.

Table II. Name-plate data for the two measured wind turbine reactors

Wind turbine power	**2.3 MW**	**3.6 MW**
Reactor rating	**2.6 MVAr**	**4.5 MVAr**
RMS current [A]	2200	3818
Inductance per phase [μH]	74	56.8
Voltage rating [V]	690	690

Both reactors were new and measured before placement in the turbines. Fig. 8 shows the 4.5 MVAr reactor as delivered from the factory.

Fig. 8. 4.5 MVAr reactor with plastic protection.

The measurement equipment was connected to the terminals of each section of the three phase reactor as shown in Fig. 9.

Fig. 9. 4.5 MVAr reactor with measurement equipment attached.

It can be seen in Fig. 9 that for the 4.5 MVAr three phase reactor each phase comprises of four parallel coils or segments. The 2.6 MVAr reactor has 3-parallel coils per phase. This kind of arrangement is used in wind turbines in order to distribute the converter current on parallel converter units. The converter is made of several parallel units, each with limited maximum current capabilities, and each comprising its own reactor, as shown in Fig. 10.

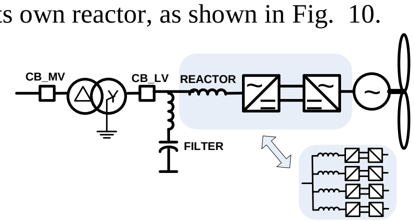

Fig. 10. Simplified single phase diagram of main electrical components in a wind turbine. In order to distribute the converter current it is composed of several parallel units, each with its own reactor.

The way to measure a segment in each phase of the reactor is shown in Fig. 11. Each measured segment was treated as a two port and thus two kinds of measurements were performed. For the measurements of the admittance, a 'self-admittance' is measured by applying voltage to a terminal and measuring the current flowing to the same terminal with the other one short-circuited. The 'mutual admittance' is measured by applying voltage to one terminal and measuring current at another one.

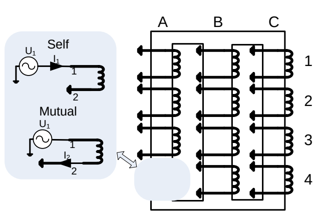

Fig. 11. Connection diagram for measurements. Two measurements are performed on coils. Self-admittance is measured by applying voltage to a terminal and measuring the current flowing to the same terminal with the other one short-circuited. The mutual admittance is measured by applying voltage to one terminal and measuring current at another one.

Only one segment is measured at a time, while the rest of the segments in the reactor, as well as the core, are grounded.

Fig. 12 shows chosen 24 measurements, performed on different segments of the 2.6 MVAr and 4.5 MVAr reactors.

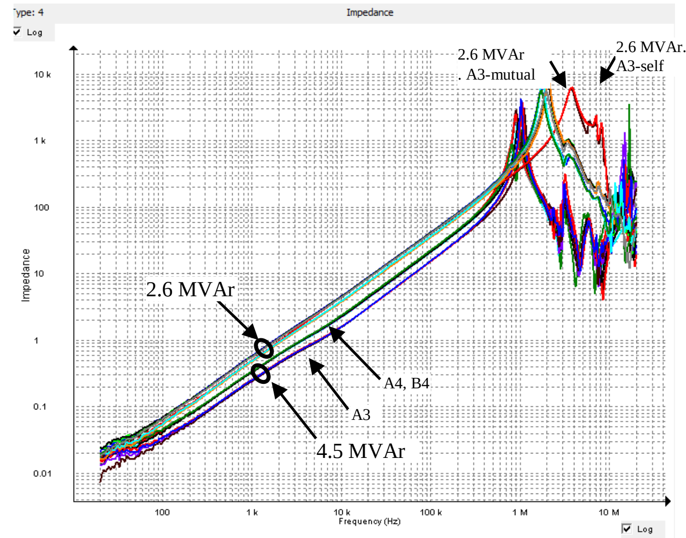

Fig. 12. Measured impedances of the 2.6 MVAr and 4.5 MVAr reactors up to 25MHz. Letters A and B in the name of a measurement denote a phase (A,B and C) and a number after it denotes the segment. See also Fig. 11.

All the measured impedances have comparable shape below 1MHz, where the internal resonances appear. At low frequencies all measurements show similar characteristics. This is also true for resistances as shown in Fig. 13.

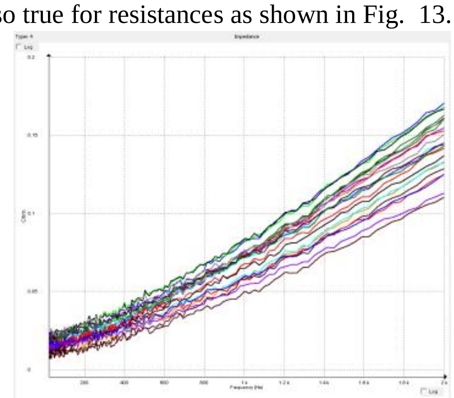

Fig. 13. Measured resistances of the 2.6 MVAr and 4.5 MVAr reactors up to 2kHz.

In the following, only the results from the segment located in the bottom left of the 2.6 MVAr and 4.5 MVAr reactors are further analyzed, these are A4 and A3 for 4.5 MVAr and 2.6 MVAr, respectively. It has been deemed sufficient to present the results from only one segment on each wind turbine reactor, since the first resonance frequency on both components is above 1MHz. In all segment measurements, the initial resistance and inductance offset at low frequency was present.

The resistance and inductance determined by means of FRAX measurements per phase on the 4.5 MVAr reactor is shown in Fig. 14, together with the datasheet values.

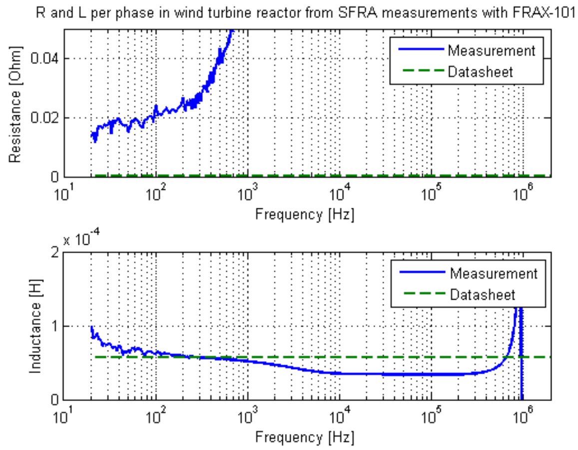

Fig. 14. 4.5 MVAr reactor resistance and inductance per phase from measurements up to 1MHz compared with the datasheet values.

In the upper subplot, where the resistance is shown, it is possible to see a large difference between datasheet information and measurements at low frequencies. The datasheet value for the resistance is in the range of milliohms and this is too small for FRAX-101 to be measured accurately. The 50 Hz resistance of FRAX-101 measurement cables is in the range of the measured value, namely approximately 0.2 Ω. On the other hand, the measured inductance is much closer to the datasheet value, with only 14% difference at 50 Hz. No additional measurements at DC or 50 Hz were performed during the measurement campaign which could validate the measurements and the datasheet values.

The resistance and inductance determined by means of FRAX measurements per phase on the 2.6 MVAr reactor is shown in Fig. 15, together with the datasheet values.

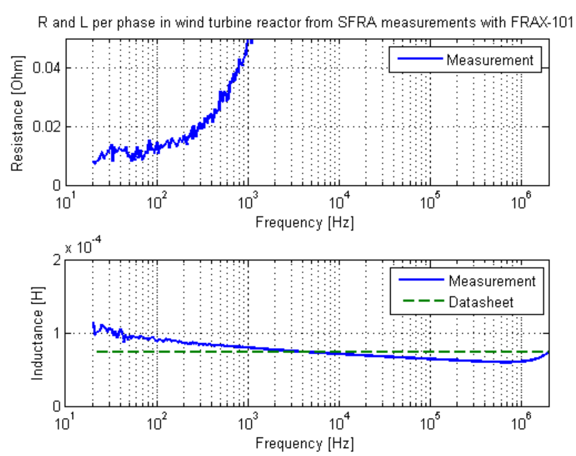

Fig. 15. 2.6 MVAr reactor resistance and inductance per phase from measurements up to 1MHz compared with the name-plate values.

No detailed datasheet information is available for this reactor, just the name plate equivalent inductance per phase.

The 50 Hz value of the measured resistance is 0.01 Ω with a shape similar to the 4.5MVAr reactor. Similarly as in the previous case, the resistance is most probably in the range of milliohms and this is too small for FRAX-101 to be measured accurately. The measured inductance is larger by 29% to the datasheet value at 50 Hz. The same inductance drop is present in both measurements.

A quadratic approximation has been applied to the normalized resistance variation of the 2.6 MVAr reactor, removing an initial offset error of 0.00366 Ω and using the datasheet resistance from the 4.5 MVAr reactor. The approximation is

$$y = Af^2 + Bf + C \qquad (2)$$

Where f is the frequency, $A = -1.4424e-006$, $B = 0.090322$ and $C = -3.6328$. The results are shown in Fig. 16.

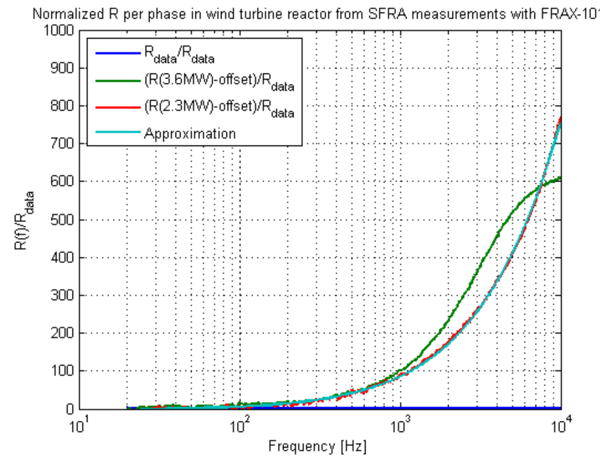

Fig. 16. Normalized resistance per phase in wind turbine reactors and quadratic approximation.

The formula is accurate for both 2.6 MVAr and 4.5 MVAr reactors up to 1 kHz when the resistance variations start to differ between the reactors.

V. Discussion

The measurements performed in the RL system using the Omicron only gave results at 6 different frequencies (50, 100, 200, 500, 750 and 1000 Hz). The impedance measurements using the Omicron were done by injecting a sinusoidal current with a certain frequency, amplitude and phase to the component and then measure the voltage across it. The phase angle between the voltage and current is recorded to calculate the impedance angle at different frequencies. Such measurement procedure is not automated, as in the case of the FRAX measurements.

In the RL-system as well as for both wind turbines reactors, the measured resistance (with FRAX and Omicron) at low frequency presents a higher value than the theoretical resistance. This is most probably due to the low accuracy of the measurement equipment for measurements of resistances in the range of milliohms. This error is consistent in all measurements.

[7] recommends using measurements or computer estimates for resistance and inductance of reactors for transients' studies. It has been show that a commercial sFRA can be used to measure inductance accurately. With such a complicated structure of modern wind turbine reactors, (see Fig. 10 and Fig. 11) knowledge of frequency characteristics of a mutual coupling between phases and segments might be of great

interest for transient modeling. However; this topic was not investigated in the study and will be a subject of future investigations.

VI. Conclusion

This paper presents results of field measurements of the frequency dependent impedance of two commercial wind turbine reactors, 2.6 MVAr and 4.5 MVAr. The measurements were performed by a commercial sweep frequency response analyzer, the performance of which was first validated by comparing measurement results from two simple systems, a coil (L-system) and a series combination of coils and resistors (RL-system), with the results obtained by means of two other high precision instruments. High accuracy of the instrument was confirmed.

The reactors were produced by different manufacturers and due to the power level and converter current limits each phase was divided into several parallel segments, 4 - for 4.5 MVAr and 3 – for 2.6 MVAr. The impedance of chosen sections of both reactors was measured in a frequency range from 20 Hz to 20 MHz and showed comparable characteristic. The resonance frequencies in all measured segments were similar for respective type of measurement and for 4.5 MVAr reactor it was around 1 MHz and 2.6 MVAr reactor – 2 MHz.

Additionally, a quadratic approximation has been done for the normalized resistance variation of the 2.6 MVAr reactor in frequencies from 20 Hz to 10 kHz. In frequencies below 1 kHz the normalized resistance is nearly identical for both reactors. Such approximation can be used for harmonic or medium-frequency studies.

VII. References

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