A method to detect the position of internal short circuit in power transformers

A. H. Soloot, M. Khanali, H. K. Hoidalen, S. Jayaram

Abstract--**wind-farm transformers are exposed to high rates of failure. Internal faults have been experienced in such transformers in many of the failure cases. Developing a method to detect the location of internal short circuits inside the transformer winding can be helpful for a more cost-effective repair and enhancing the transformer design. This paper suggests using sweeping frequency response analysis to estimate the location of an internal fault inside the winding. To this purpose, frequency responses of a 500 kVA 11/0.24 kV wind turbine transformer are examined at situations of having internal faults at different locations. The results show that there are systematic changes in the frequency response of the transfer voltages, i.e. HV/LV or LV/HV, when the position of internal fault moves from inner layers of the winding to the outer layers. The input impedances from HV and LV terminals are not sensitive to the location of short circuits in the frequency range of 10 kHz-10 MHz.**

Keywords: **Transformer, Frequency response analysis, wind energy, fault diagnosis.**

I. Introduction

Wind energy is delivered to the power grid by different types of energy conversion systems. Today, variable speed wind turbine generators, which are connected through a full power converter; defined as the Type 4 converters, are increasingly implemented in wind-farms [1]. Power converters used in this type of power plants generate power electronics switching transients which impose on wind turbine transformer [2]. In addition to the switching transients of the converter, oscillatory voltages generated by the operations of neighboring circuit breakers also impact the transformer significantly [3]. This means that although this arrangement, positively, adds the controllable characteristics and decouples the generator from the grid by a DC-link but it necessitates certain considerations about transformers which are installed in such power plants.

Due to the aforementioned reasons, recently, high numbers of wind turbine transformer failures (among them, internal faults) have been reported by wind farm developers and operators [4,5]. This fact necessitates a scrutinized research on internal faults in wind farm transformers. There are two main tasks in internal fault diagnosis: to detect the occurrence of the fault, and to estimate the location of the fault. Addressing the detection of fault occurrence, different methods have been used for many years [6]. Nevertheless, locating the position of internal faults has been of less focus in recent research.

It is obviously helpful to detect the location of the internal fault as it can lead to reducing cost and time of the repair as well as reinforcing the insulation of vulnerable spots. This would be even more important for offshore wind farm transformers due to their high repair/maintenance costs [7].

In an attempt to establish a method for locating the internal faults, this paper investigates the effects of fault location on the frequency response of transformer parameters, i.e. input HV impedance and transfer voltages. It is shown that moving the fault to different locations in the winding changes the frequency response of transformer parameters with certain patterns. These systematic changes in the frequency responses can be utilized to predict the location of internal faults. To recognize the mentioned patterns, the frequency responses of faulty transformers are compared with the frequency responses of a healthy transformer. The trends are analyzed by both qualitative and quantitative approaches.

II. Methodology

Transformer condition analysis has been the subject of many research studies. Different methods have been proposed to investigate the condition of transformer winding structure as well as bushings and insulation system [8]. One of the most prominent techniques which is used individually or in combination with other techniques is sweeping frequency response analysis (SFRA). SFRA method is widely used to detect the displacements of windings on transformer core, winding deformations, etc. [9]. SFRA, generally, is a feature that can be utilized as transformer's unique fingerprint. In other words, any physical and/or chemical changes in transformer structure (one of which internal fault) reflect on the frequency spectra of the transformer parameters. Frequency response measurement is nowadays easily achievable by frequency response analyzers. Analyzing the changes in frequency response spectra and finding the causes of the changes can be done based on electromagnetic theories.

Two categories of parameters are measured in SFRA method: transfer voltages (V_{out}/V_{in}) and input impedance (V_{in}/I_{in}). As it can be concluded from the literature [10], the transfer voltages have no direct relation with the input impedance measurement. Both of these parameters are adopted in this research for the diagnosis of fault location.

Artificial short circuits are implemented in the transformer winding to simulate the internal faults at different layers. For each short circuit, frequency responses of transfer voltage and

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input impedance are measured, and compared with the frequency responses of other short circuits. Also, all the frequency responses of the transformer with different fault locations are compared with the frequency response of the healthy transformer. The comparison is done via statistical parameters along with visual observations of frequency spectra.

Considering $R_0(f)$ as the frequency response of a healthy transformer and $R_{sc\_1}(f), R_{sc\_2}(f), \ldots, R_{sc\_k}(f), \ldots, R_{sc\_n}(f)$ as frequency responses of that transformer with fault numbers $1, 2, \ldots, k, \ldots, n$, the formula for computing the correlation coefficient can be derived as :

$$CF(k) = \frac{\sum_{f=f_{min}}^{f_{max}} R_{sc\_k}(f) \cdot R_0(f)}{\sqrt{\sum_{f=f_{min}}^{f_{max}} (R_{sc\_k}(f))^2 \cdot \sum_{f=f_{min}}^{f_{max}} (R_0(f))^2}}$$

f_{min} is the lower frequency limit of the measurement; f_{max} is the upper frequency limit of the measurement; The correlation coefficient always ranges between -1 and 1, with 1 or -1 indicating perfect correlation (all points would lay along a straight line in this case). A correlation value close to 0 indicates no association between the variables.

III. Experimental

A 500 kVA 11/0.240 kV transformer, equipped with several connection leads along the winding is designed and produced for this study. The design of this custom made transformer facilitates the implementation of artificial internal faults at different layers of the transformer winding. FRA measurement is performed for each short circuit case.

Fig. 1 shows the layout of the transformer with layer winding. The position of the 25 connection leads along the layer winding is also marked with black dots.

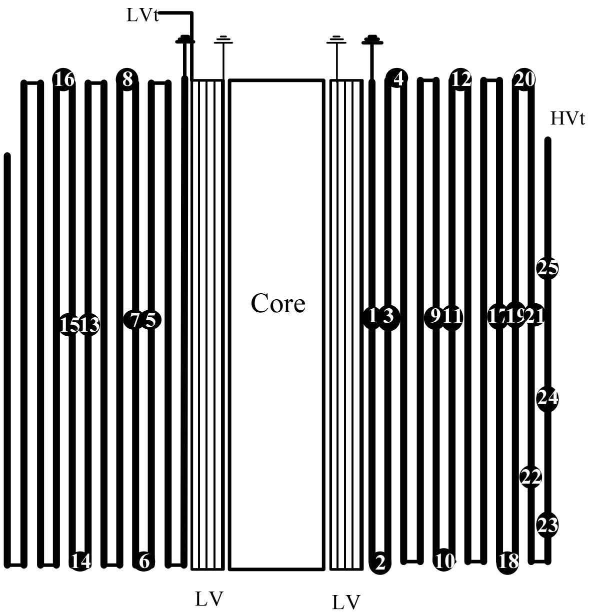

Fig. 1. The layout of the 500 kVA layer winding with locations of connections leads.

TABLE 1
FAULT NUMBERING BASED ON THE POSITION OF SHORT CIRCUITS ACCORDING TO FIG. 1

Fault Number	Location of Short Circuit Between Connection Leads
1	1 & 3
2	3 & 5
3	5 & 7
4	7 & 9
5	9 & 11
6	11 & 13
7	13 & 15
8	15 & 17
9	17 & 19
10	19 & 21

The frequency response of the transferred voltages to LV terminals is measured from 10 kHz to 10 MHz with Agilent network analyzer E5061B and Tektronix P2220 probes. The voltage probes are used with x10 attenuation which is appropriate for voltage measurement up to 200 MHz. For measuring the input impedance of HV and LV windings, the Ionphysics® current sensors CM-100-6L-IR50 is used (positioned in the gray box in the setup shown in Fig. 2). The sensitivity analysis of the internal resonances to voltage and current measurement probes are studied in [11]. By means of the aforementioned network analyzer, the current and voltage probe, the internal resonance behavior of the 500 kVA layer winding is studied in [12].

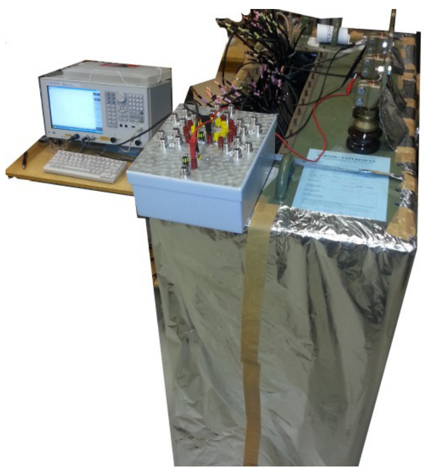

Fig. 2. The experimental setup for the measurement of the frequency response of input impedance.

IV. Results and Discussion

Frequency response measurements are performed for four parameters of the transformer: voltage transfer ratio from LV to HV (V_{HV}/V_{LV}), voltage transfer ratio from HV to LV (V_{LV}/V_{HV}), input impedance from HV side (Z_{HV}) and input impedance from LV side (Z_{LV}). For each parameter, magnitude and phase angle of transfer functions are recorded.

In all 3D graphs, Z axis indicates the magnitude (db) or

Cos(φ) of frequency response, Y axis indicates the frequency and X axis indicates the fault number.

A. V_{HV}/V_{LV}

As it can be seen in Fig. 3, frequency responses of faults #1 to #5 show a resonant frequency at 60 kHz while frequency responses of faults #8 and #9 are on their peak at 200 kHz. This observational recognition can be used as a differentiator between the faults #1-#5 and, faults #8 and #9. Aside from the aforementioned noticeable differences, the frequency responses of different fault locations do not differ significantly.

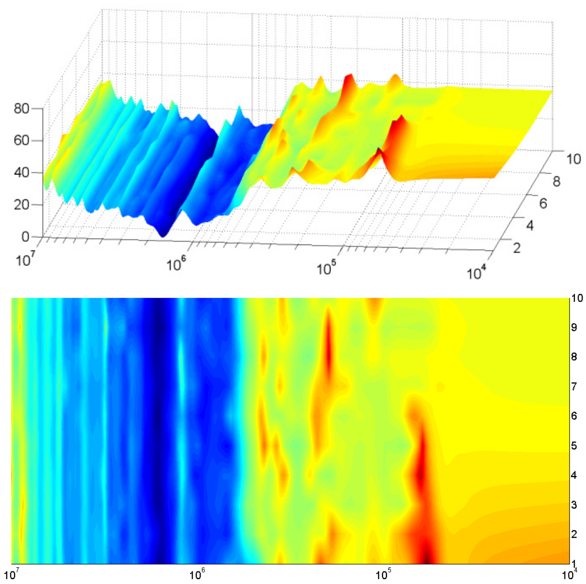

Fig. 3. V_{HV}/V_{LV} frequency response (magnitude) for faults #1 to #10 top: 3D view, bottom: top view (colored map)

In addition to the observational recognition (qualitative analysis), correlation factor as a quantitative measure can be helpful to compare the frequency responses of different fault locations. As it is shown in Fig. 4, correlation factor between the frequency responses of the healthy winding and the faulty winding increases when the fault is in outer layers (fault number increases).

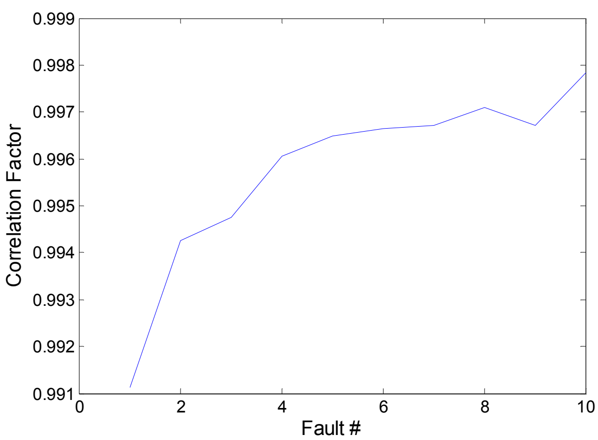

Fig. 4. Correlation factor between the V_{HV}/V_{LV} frequency response (magnitude) of the healthy transformer and those of the transformer with faults at different locations.

Fig. 5 shows the *Cos(φ)* versus frequency for different fault locations, where *φ* is the phase angle of the frequency response. Fig. 5 is a good example of cases in which *Cos(φ)* frequency response adds valuable information to the output of magnitude frequency response. As it is shown in Fig. 5, only faults #1, #3 and #5 have resonant frequency at 60 kHz. Fault #9 has a resonant frequency at 200 kHz. Fig. 6, however, shows similar trend as it exist in Fig. 4.

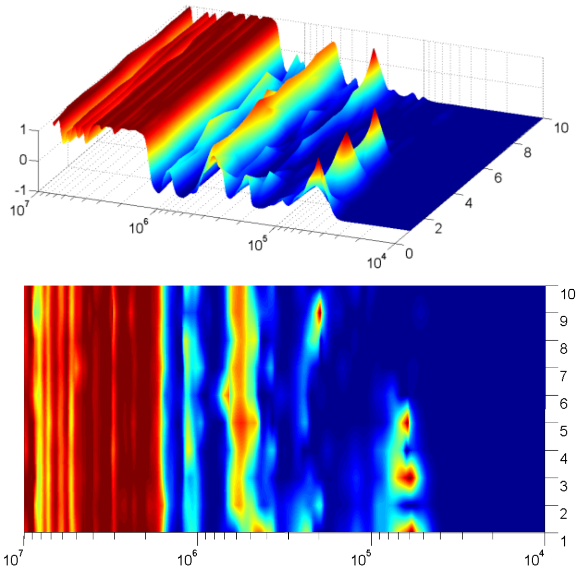

Fig. 5. V_{HV}/V_{LV} frequency response (*Cos(φ)*) for faults #1 to #10 top: 3D view, bottom: top view (colored map)

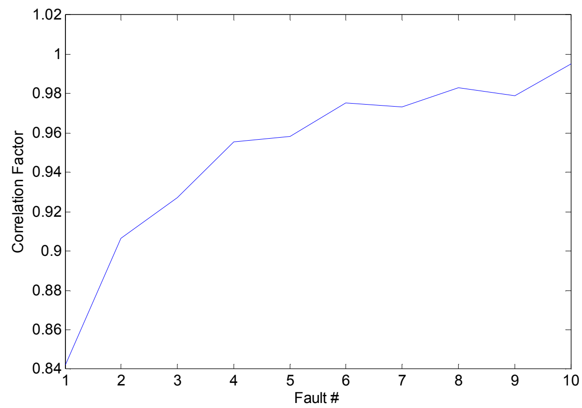

Fig. 6. Correlation factor between the V_{HV}/V_{LV} frequency response (*Cos(φ)*) of the healthy transformer and frequency responses of the transformer with faults at different locations.

B. VLV / VHV

Fig. 7 shows the transfer voltage from HV to LV for different fault locations. Similar to HV/LV, 60 kHz is an important frequency here too. Fault locations 1-5 show their first resonance frequency at 60 kHz. Fault location 5-9 show a resonance frequency at 200 kHz. Correlation factor graph (Fig. 8) also verifies the above observation as it does not follow a rising or falling trend but fluctuates around 0.89. The correlation factor graph in Fig. 8 is quite different from that in Fig. 4.

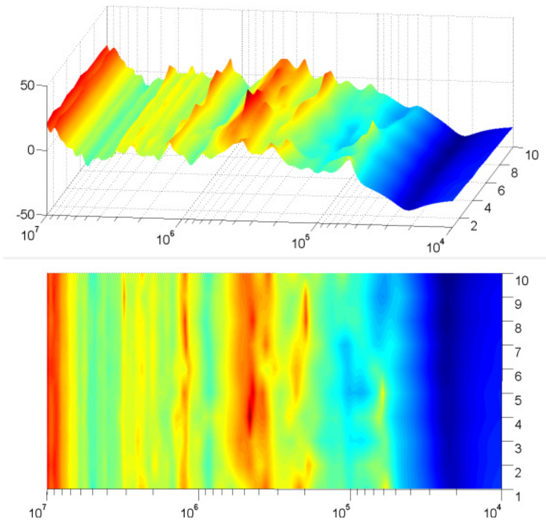

Fig. 7. V_{LV}/V_{HV} frequency response (magnitude) for faults at layers #1 to layers #10 top: 3D view, bottom: top view (colored map)

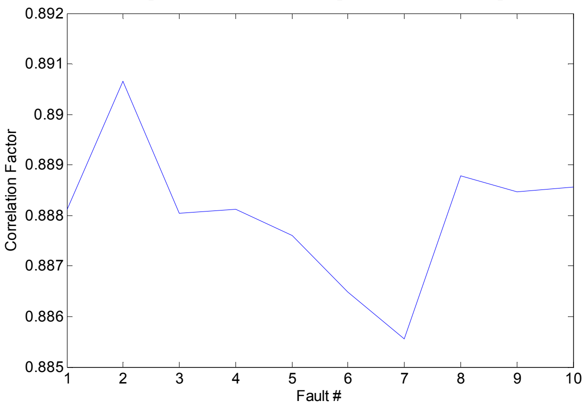

Fig. 8. Correlation factor between the V_{LV}/V_{HV} frequency response (magnitude) of the healthy transformer and frequency responses of transformer with faults at different locations.

Fig. 9 is similar to Fig. 5, especially in its crucial points. This similarity was expectable as these two responses are inverted versions of each of other and the *Cos(φ)* of these two transfer voltages should be equal. The increasing trend in Fig. 10 is similar to that in Fig. 6 while the correlation values are quite lower.

C. Z_{HV}

Frequency response of Z_{HV} magnitude is a good example of a parameter which is not too sensitive to fault location. As it can be seen in Figures 11 and 13, changing the fault location does not make a big distinction between the frequency responses. This fact can be also confirmed by correlation factor graphs (figures 12 and 14). Although a generally rising trend is seen in the correlation factor value by increasing the fault number, the difference between the adjacent correlation factors is very low (in range of 0.001). Compared to the previous correlation factors, correlation factors in figures 12 and 14 can be considered constant.

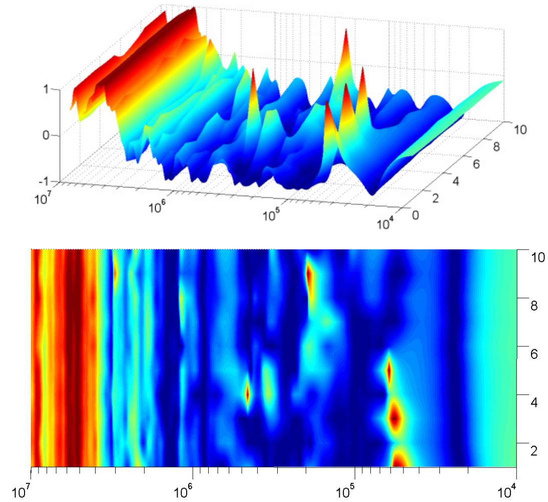

Fig. 9. V_{LV}/V_{HV} frequency response (*Cos(φ)*) for faults at layers #1 to layers #10 top: 3D view, bottom: top view (colored map)

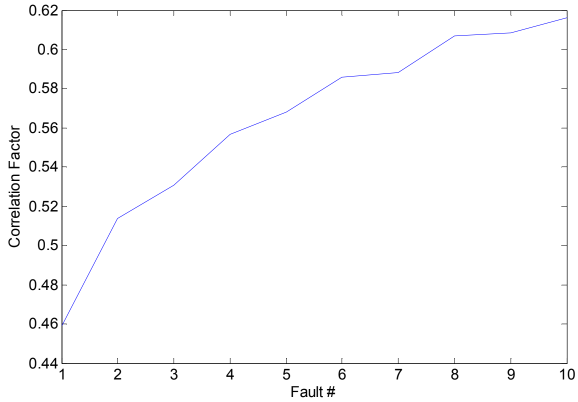

Fig. 10. Correlation factor between the V_{LV}/V_{HV} frequency responses (*Cos(φ)*) of the healthy transformer and frequency responses of transformer with faults at different locations

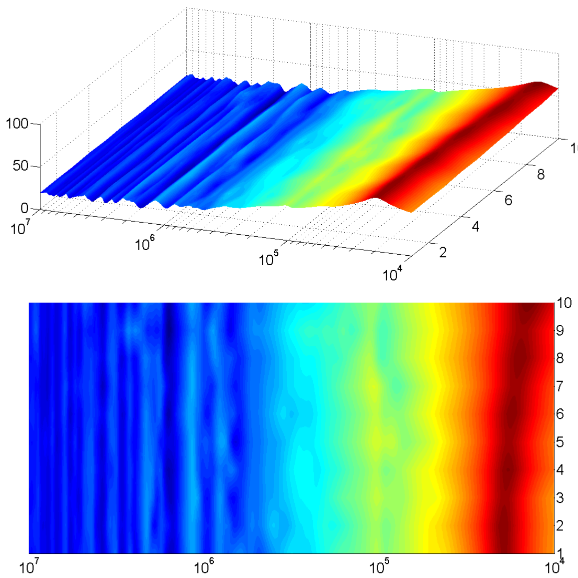

Fig. 11. Z_{HV} frequency response (magnitude) for faults at layers #1 to #10 top: 3D view, bottom: top view (colored map)

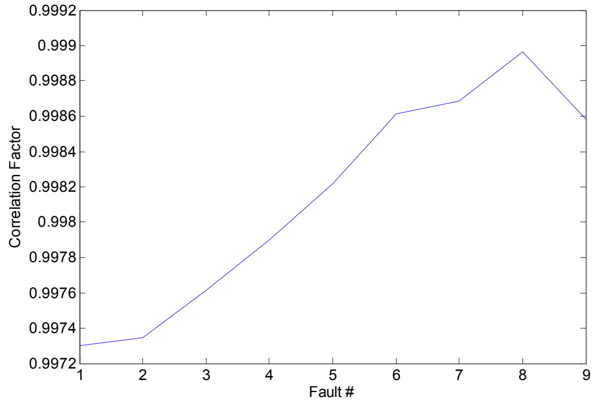

Fig. 12. Correlation factor between the Z_{HV} frequency responses (magnitude) of the healthy transformer and frequency responses of transformer with faults at different locations

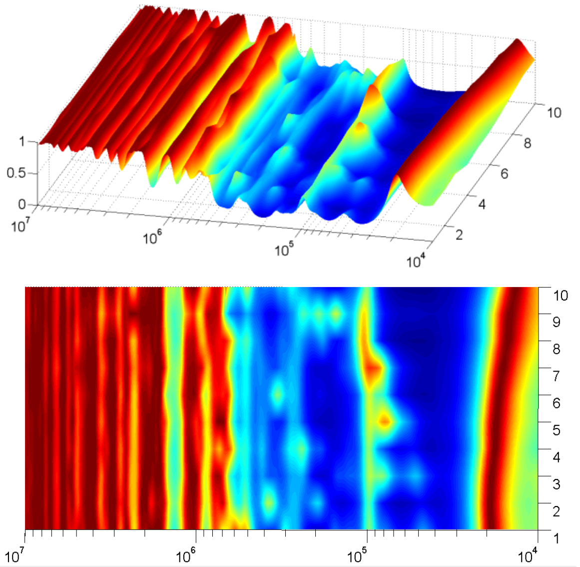

Fig. 13. Z_{HV} frequency response ($Cos(\varphi)$) for faults at layers #1 to #10 top: 3D view, bottom: top view (colored map)

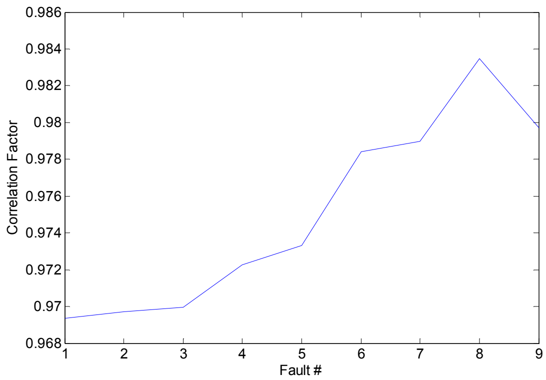

Fig. 14. Correlation factor between the Z_{LV} frequency responses ($Cos(\varphi)$) of the healthy transformer and frequency responses of transformer with faults at different locations

D. Z_{LV}

Fig. 15 shows the frequency response of the input impedance magnitude from LV side. Similar to Z_{HV} magnitude, the pattern of Z_{LV} magnitude does not show a notable sensitivity of this parameter to fault location. On the quantitative part of study, it is observed in Fig. 16 that the correlation factor decreases by moving the fault to the outer layers. This decrease is however not significant.

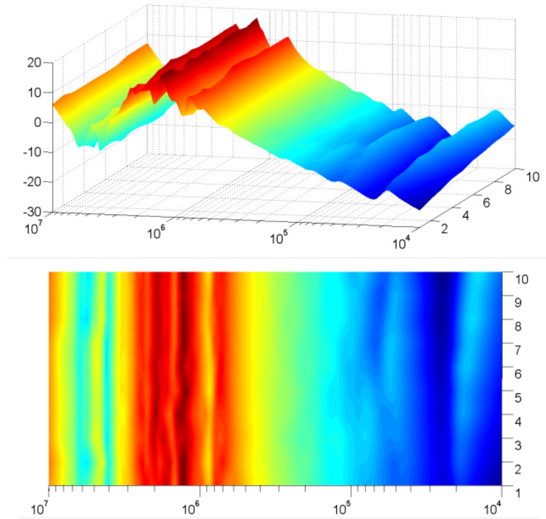

Fig. 15. Z_{LV} frequency response (magnitude) for faults at layers #1 to #10 top: 3D view, bottom: top view (colored map)

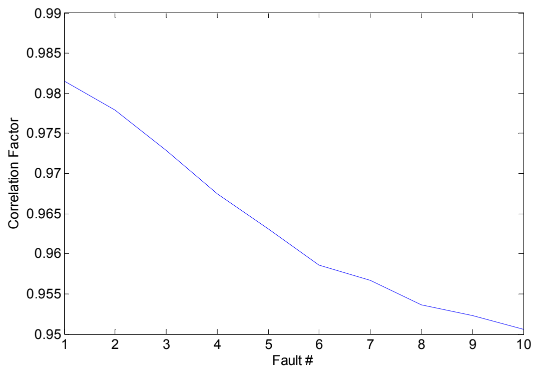

Fig. 16. Correlation factor between the Z_{LV} frequency responses (magnitude) of the healthy transformer and frequency responses of transformer with faults at different locations.

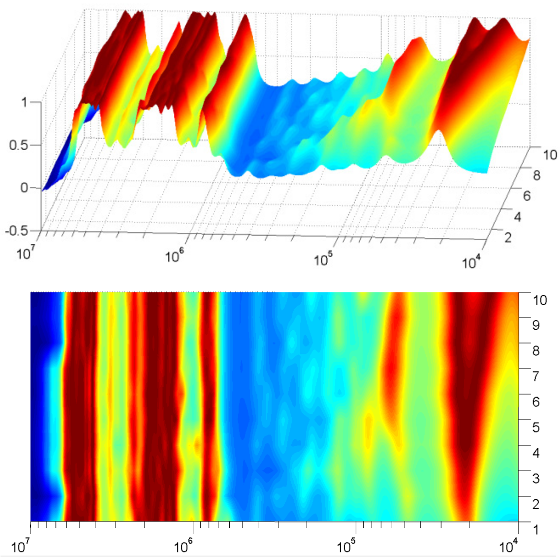

Fig. 17. Z_{LV} frequency response ($Cos(\varphi)$) for faults at layers #1 to #10 top: 3D view, bottom: top view (colored map).

Cos(φ) frequency response in Fig. 17 shows a better pattern compared to Cos(φ) of Z_{HV} (Fig. 13). Faults in layers close to core (1-5) show one resonant frequency at 20 kHz while the other faults show two resonant frequencies around 20 kHz. Fig. 18 shows a slight incremental trend for correlation factors of frequency responses of faults locations.

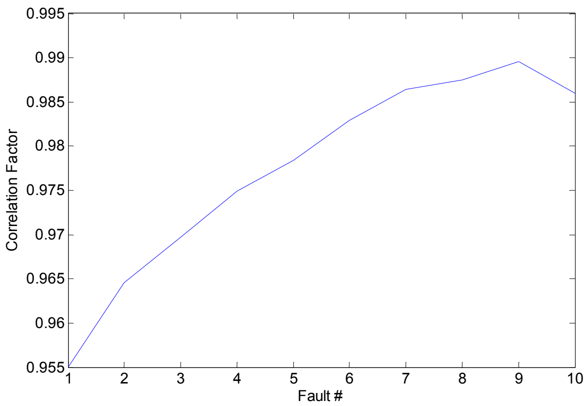

Fig. 18. Correlation factor between the Z_{LV} frequency responses (magnitude) of the healthy transformer and frequency responses of transformer with faults at different locations

V. CONCLUSIONS

This paper aims to address the detection of internal faults position in wind turbine transformers. By means of Sweeping Frequency Response Analysis (SFRA), the impact of internal fault positions on the transfer functions, e.g. input impedance and transfer voltages are studied. Internal faults are artificially implemented in a 500 kVA 11/0.240 kV transformer through connection leads in its winding.

It is found that transfer voltages, i.e. HV/LV and LV/HV, are sensitive to the position of the internal faults while input impedance of HV and LV winding have not considerable sensitivity to the position of internal faults. Transfer voltage HV/LV reveals that if the first resonant frequency of the 500 kVA transformer, which has internal fault, is at 60 kHz, the internal fault is close to core. The first resonant frequency at 200 kHz can be interpreted as internal fault at position 8 or 9. This pattern is also repeated for LV/HV transfer.

In addition to the qualitative observational analysis, the correlation coefficient is applied as a quantitative measure to distinguish the location of internal faults. Correlation factor between the frequency responses of the healthy winding and the faulty winding are computed for the amplitude and *Cos(φ)* of the input impedance and transfer functions. For instance, in the case of *Cos(φ)* of LV input impedance, the correlation factor increase as the location of internal fault is moved to outer layers.

The presented results can be benefited by wind turbine operators to consider on-site FRA measurements to monitor the transformers and diagnose the internal faults occurrence. The offline FRA measurements and comparison with FRA of the healthy transformer can also be used to distinguish the position of internal faults.

VI. REFERENCES

[1] P. W. Carlin, A. S. Laxson and E. B. Muljadi, “The History and State of the Art of Variable-Speed wind Turbine Technology”, National Renewable Energy Laboratory/National Wind Technology Center, 1617 Cole Boulevard, Golden, CO 80401, USA

[2] Hopkinson, P. J.; “Wind Power Transformer Design”, PEHVOLT Inc. 2013 Life of a Transformer™ Seminar February 18-21, 2013, San Diego, California USA

[3] A. H. Soloot, H. K. Hoidalen and B. Gustavsen, ”Resonant overvoltage assessment in offshore wind farms via a parametric black-box wind turbine transformer model”, Wind Energy. DOI: 10.1002/we.1748.

[4] J. Larsen, H. C. Soerensen, E. Christiansen, S. Naef, P. Vølund, “Experiences from Middelgrunden 40 MW Offshore Wind Farm”; Copenhagen Offshore Wind 26-28 October 2005.

[5] B. Gustavsen, "Study of Transformer Resonant Over-Voltages Caused by Cable-Transformer High-Frequency Interaction" Power Delivery, IEEE Transactions on , vol.25, no.2, pp.770,779, April 2010

[6] S. S. Patil and S. E. Chaudhari, “An Attempt to Investigate the Transformer Failure by using DGA and SFRA Analysis”, In proc. of IEEE 10th international Properties and Applications of Dielectric Materials (ICPADM), July 2012.

[7] A.H. Soloot, H. K. Hoidalen and B. Gustavsen,” The Effect of Winding Design on Transformer Frequency Response with Application on Offshore Wind Farm Energization”, in proc. Of International Conference on Renewable Energy Research and Applications (ICRERA2012), pp. 1-5, Nagasaki, Japan, November 2012.

[8] Khanali, M.; Jayaram, S.; Cheng, J., "Effects of voltages with high-frequency contents on the transformer insulation properties," Electrical Insulation Conference (EIC), 2013 IEEE , vol., no., pp.235,238, 2-5 June 2013

[9] F. H. Wang, J. Xu, Z. J. Jin, and S. S. Gui, “Experimental research of vibration sweep frequency response analysis to detect the winding deformation of power transformer”, in proc. Of IEEE Transmission and Distribution Conference and Exposition, 2010.

[10] J.R. Secue, E. Mombello, Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers, Electric Power Systems Research, Volume 78, Issue 6, June 2008, Pages 1119-1128, ISSN 0378-7796,

[11] A.H. Soloot, H.K. Hoidalen, B. Gustavsen, “Modeling of wind turbine transformersfor resonant overvoltage —sensitivity analysis”, in. proc. International Conference on Electrical Machines and Systems 2013 (ICEMS 2013), Busan, Korea,2013.

[12] A.H. Soloot, H.K. Hoidalen, B. Gustavsen, “Influence of the winding design of wind turbine transformers for resonant overvoltage vulnerability”, IEEE trans. on Dielectric and Electric Insulation, Vol. 22, issue. 2, pp. 1250-1257, April 2015.