Detection of winding inter-turn faults

Detection based on frequency response analysis - Part III

ABSTRACT

This article deals with inter-turn fault detection in the transformer winding, inter-turn fault which occurs due to insulation degradation between one or more sequential turns of the winding. If the fault is not detected at the earliest stage, it propagates to the nearby turns of the winding during certain period of time and it causes irreversible damage to the winding. Therefore, it is necessary to detect inter-turn fault to save the transformer from catastrophic failure.

KEYWORDS

detection, fault factor, inter-turn, SFRA, transformer

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An inter-turn fault is one of the leading causes of power transformer failures; it can be detected using sweep frequency response analysis

1. Case studies – Detection of fault in layer windings using SFRA

Frequency response analysis can be extended to single and multi-layer windings. At the same time, the fault factor characteristics are obtained for different fault percentages.

1.1. Detection of fault in single-layer winding – measurement results

Sweep frequency response analysis (SFRA) is performed on a single-layer 1000-turn winding from 10 Hz to 25 MHz. This winding has 20 sections where each section consists of 50 turns. Tappings were available at each section end in order to create inter-layer fault. For instance, 5 % fault is created by shortening one section, which corresponds to a short circuit of 50 turns. Fig. 1a and 1b show single-layer winding and a schematic diagram of single-layer winding.

Figure 1a. Single-layer winding

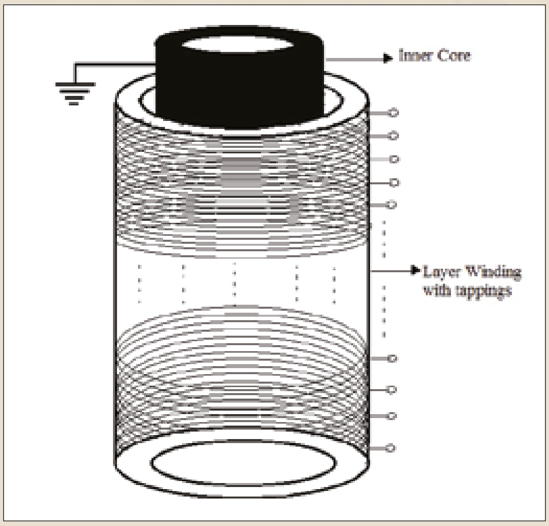

Figure 1b. Schematic diagram

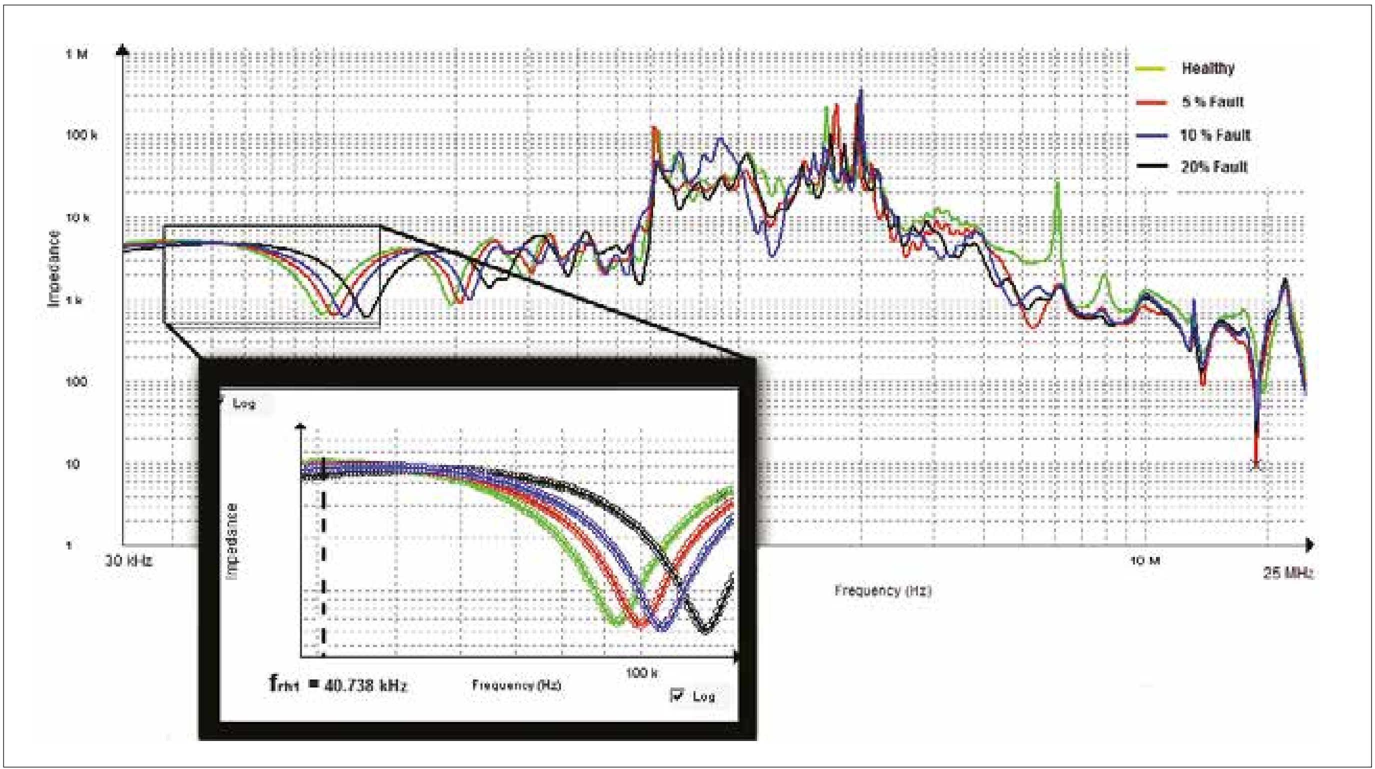

Figure 2. Impedance characteristics for healthy winding and 5 %, 10 % and 20 % faults at different locations along the single-layer winding

Sweep frequency response analysis is performed from 10 Hz to 25 MHz

Fig. 2 shows the measured impedance characteristics for healthy winding and 5 %, 10 % and 20 % faults at different locations along the winding. The first resonant frequency of the healthy winding is f_{rh1}= 40.738 kHz. The impedance characteristic shows a reduction in the impedance at this frequency depending on the location of the fault.

Fig. 3 shows the fault factor characteristics for 5 %, 10 % and 20 % of inter-turn fault in the winding. The curve shifts upwards as the percentage of fault decreases. This curve is symmetrical with respect to the centre of the winding section and provides reliable information about fault detection.

1.2. Detection of fault in multi-layer winding - measurement results

SFRA is performed on the multi-layer

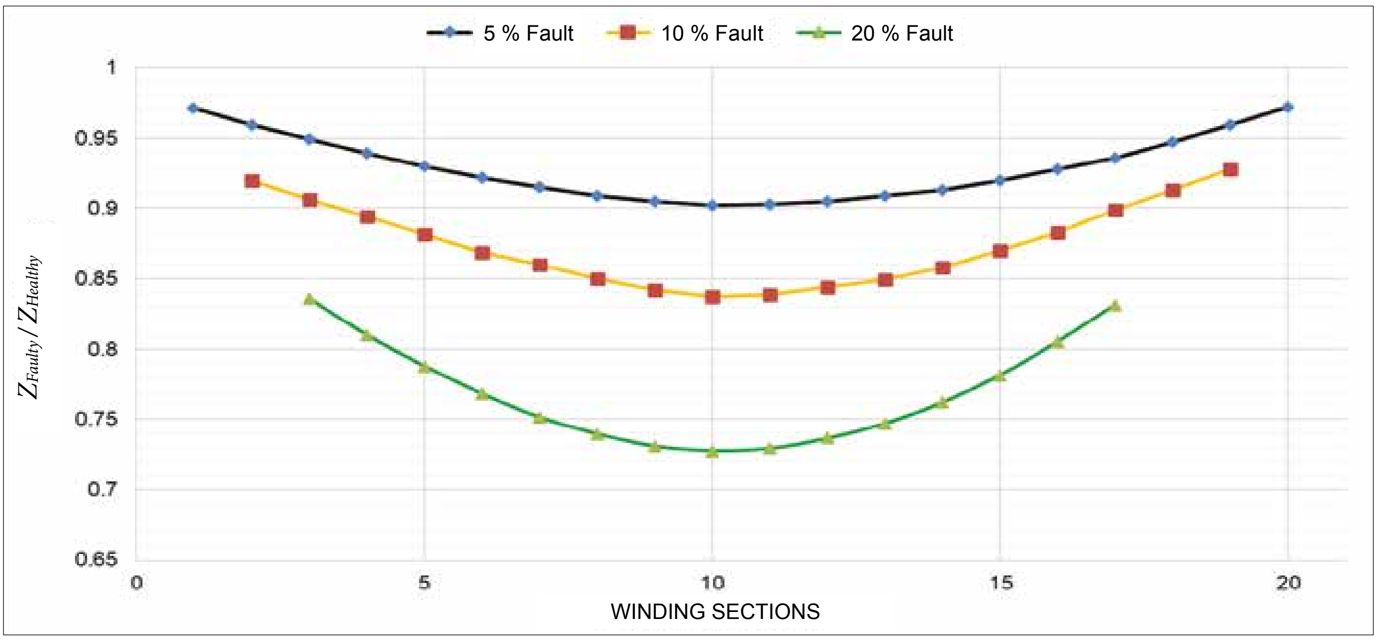

Figure 3. Fault factor for 5 %, 10 %, 20 % faults vs layer sections for different percentage of faults at different locations

Figure 4a. 10 section multi-layer winding

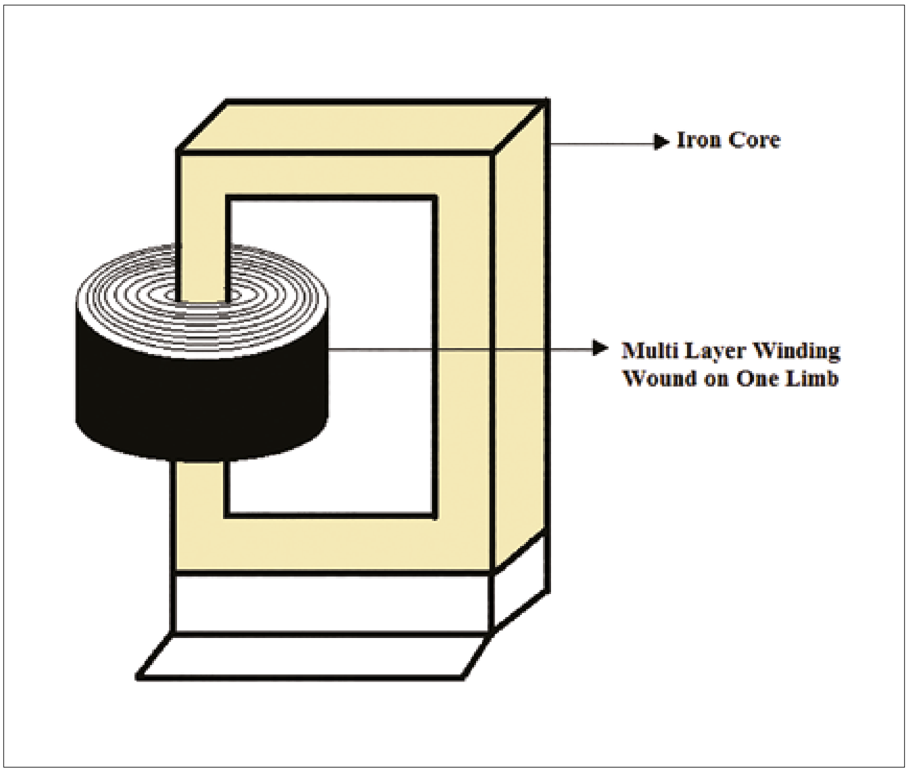

Figure 4b. Multi-layer winding schematic diagram

windings with 10 layers from 10 Hz to 25 MHz. Each layer consists of 200 turns. Tappings were brought out at every section in order to create inter-layer short circuit faults. For instance, 10 % inter-layer fault is created by shortening 2 consecutive layers in a multi-layer winding. Fig. 4a and 4b show the 10 section multi-layer winding and schematic diagram of the 10 section multi-layer winding.

Fault factor is a ratio of the impedances of faulty and healthy winding at the first resonant frequency of the winding; it is a quantity used for the inter-turn fault detection

The sweep frequency response of the winding changes depends on the extent of the fault. Fig. 5 shows the impedance characteristics for healthy and 10 %, 20 % and 30 % inter-layer faults along the first section in the winding.

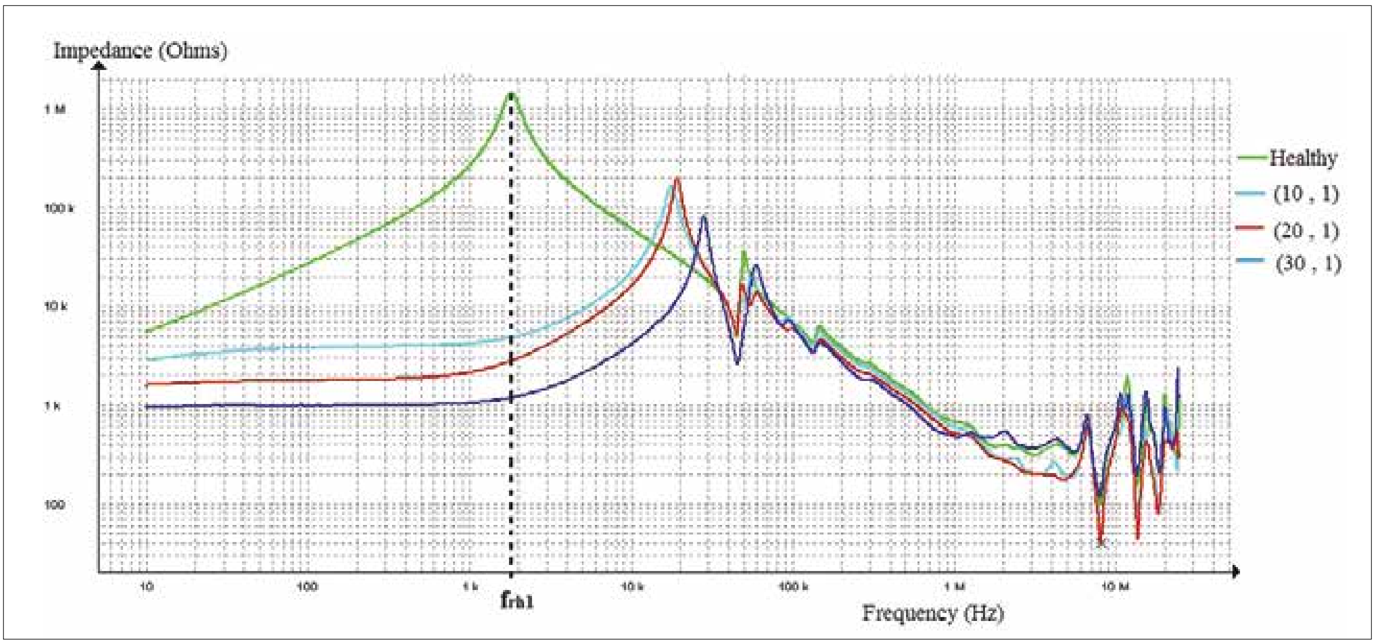

Figure 5. Impedance characteristics for healthy and percentage of faults along the multi-layer winding

> **SFRA method can be used for detecting the inter-turn faults for both single-layer and multi-layer winding**

Change in the fault factor values for 10 %, 20 %, 30 % of inter-layer faults at different locations along the winding is shown in Fig. 6. It is clear from the figure that the location and extent of fault changes when there is a corresponding change in the fault factor values. As the percentage of fault increases, the fault factor curve shifts downwards. Thus, it can be noted that the 20 % fault curve lies within the 10 % fault curve and the 30 % fault curve. This factor value is symmetrical for each percentage of faults, and this property is used for detection of an inter-layer fault in the layer winding.

2. Effect of static end ring, grounded inner core and aluminium grounded tank on detection of the inter-turn fault in continuous disc winding

The objective of this section is to check the influence of the shunt capacitance, as well as the series capacitance, on the frequency response trace of the winding, and thus on the detection of the inter-turn fault.

Transformer winding resistance, self and mutual inductance as well as the series and shunt capacitances, have their own impacts on the spectrum response. From a physical point of view, winding inductances, as well as capacitances, play a major role in the formation of the frequency response trace. At low frequencies, transformer winding inductances are more dominant as inductive reactance of the transformer winding is considerably greater than capacitive reactance. As the frequency increases, inductive reactance will take the values high enough to be neglected. At the same time, capacitive reactance becomes gradually a major player in the formation of the frequency response trace. This study concentrates on the shunt capacitance influences on the frequency response spectrum oscillations and explores the shunt capacitance contribution in the FRA spectrum. The contribution of this study is generally focused on the transformer model winding with an isolated tank, grounded tank on LV and HV windings in order to check any influence on the frequency response fluctuations [1].

Any changes in the values of inductance or capacitances, as well as winding length, may lead to changes in resonant frequencies [2]. The magnitude of the series capacitance of the windings has an important effect on the impulse voltage distribution and the stresses along the windings. By increasing the series capacitances of the windings, the impulse voltage distribution α becomes more linear, and the stress on the winding is reduced.

$$\alpha = \sqrt{\frac{C_g}{C_s}} \qquad (1)$$

Where:
α - Voltage distribution parameter
C_g - Capacitance between winding and tank
C_s - Series capacitance of winding

To improve the transient voltage distribution along the transformer winding, it is necessary to make the initial voltage distribution constant α as low as possible. One way of accomplishing this is to increase Cs [3]. The static end ring (SER) is placed over the top of the winding and connected to the line terminal of the winding. A spacer is inserted in-between the SER and the top of the winding to provide proper clearance. In practical cases, a SER is placed over the top of the winding, which reduces the stress locally during the initial voltage distribution.

By providing a large equipotential surface with a good corner radius, the SER reduces the stress concentration at the line end. The SER changes the series capacitance

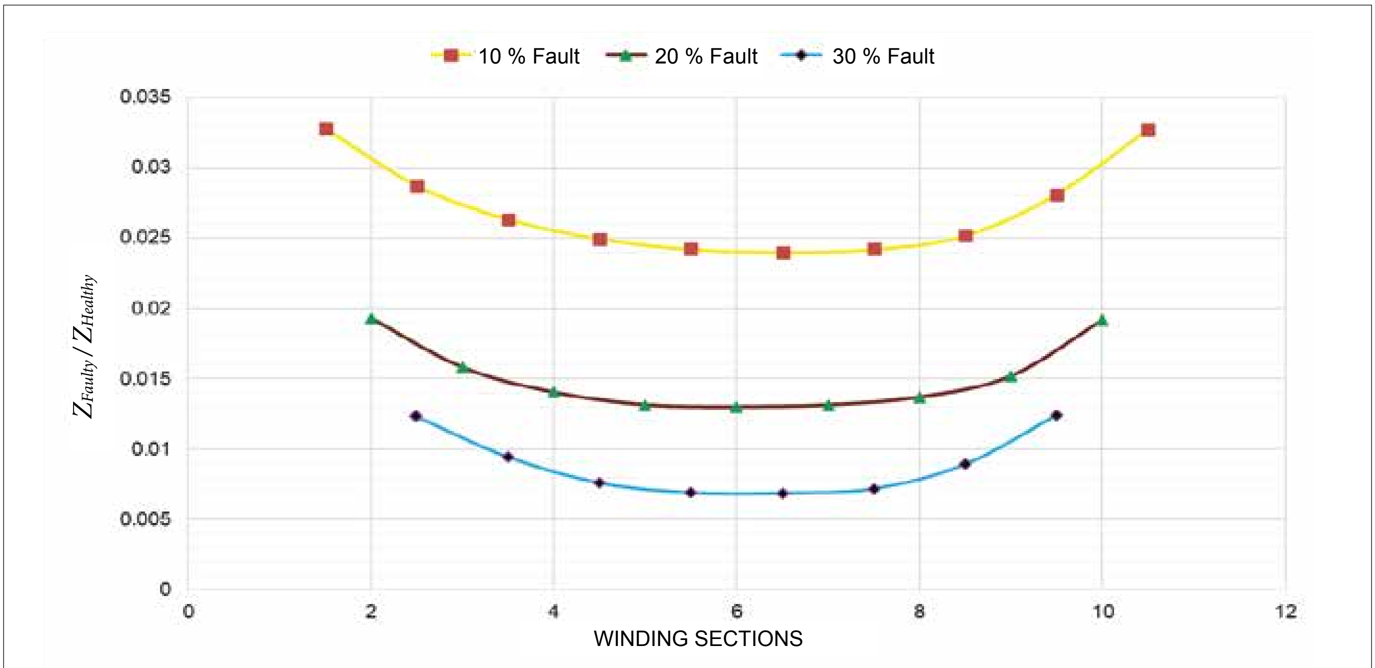

Figure 6. Fault factor vs layer sections in multi-layer winding with 10 layers for 10 %, 20 % and 30 % inter-layer fault

C_s of the winding. A grounded aluminium tank is placed around the winding to provide the shunt capacitance C_g between the winding and the tank. Fig. 7 shows the continuous disc winding in the presence of the SER, grounded aluminium tank and grounded inner core. The deviations of the FRA traces come through the capacitance changes of the winding with respect to the grounded inner core, SER and grounded tank.

The following two cases are considered to check the influence of the shunt capacitance C_g due to the grounded tank and series capacitance C_s due to SER on the impedance characteristics of the winding which lead to a change in the location of the inter-turn fault. In both Cases I and II, the grounded inner core is considered for the study, and in Case II, the grounded tank is excluded from the measurement.

Case I: Continuous disc winding with a grounded tank, grounded inner core, and SER on top of the winding.

Case II: Continuous disc winding with the grounded inner core, and SER on top of the winding.

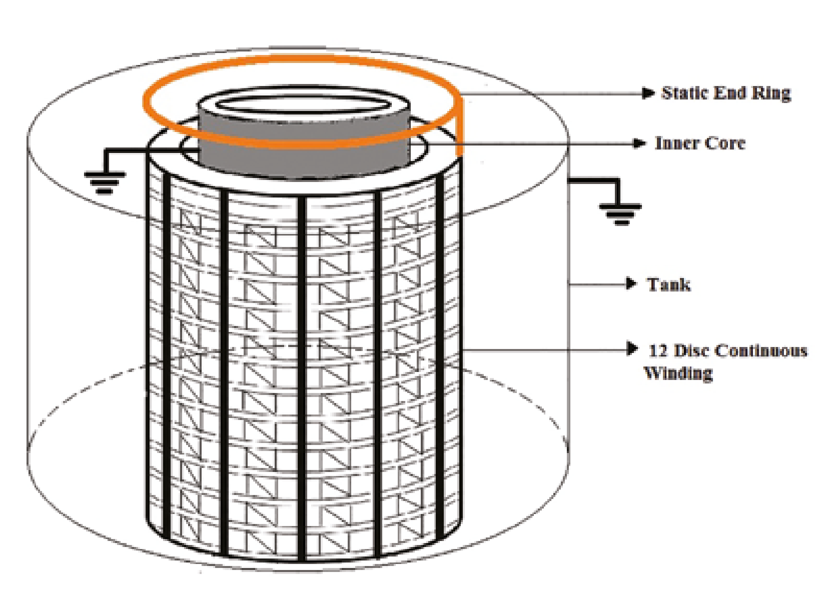

Figure 7. Schematic diagram of continuous disc winding in the presence of SER and aluminium grounded tank, grounded inner core

Presence of the static end ring has an influence on the resonant frequencies in the frequency response trace which comes from changes in the series capacitances

Deviated frequencies provided in Table 1 show the first two resonant frequency variations. In the case of the frequency response trace of the winding, C_1 is due to the presence of the grounded tank, grounded inner core and SER, and C_2 is due to the presence of the grounded inner core and SER. According to the data shown in Table 1, it is estimated that the shift in the resonant frequencies in the presence and absence of the static grounded tank and SER, the series and shunt capacitance variation is found to be 9.6 %, while the second resonant frequency reports 4.7 % variation in the capacitance.

A fault factor is calculated for continuous disc winding in the presence and absence of a grounded aluminium tank and SER. Fig. 8 - 10 show the fault factor variation in the presence and absence of the grounded tank and SER where the difference between the fault factor characteristics is very minimal.

Detection of inter-turn fault in transformer winding using SFRA – measurement summary

Methods for detection of the fault have been developed by the SFRA-based measurement on the continuous disc winding and layer windings and can be summarized as follows:

- Detection of fault with respect to the centre of the winding can be found by using fault factor characteristics.
- Fault factor characteristics are obtained for the detection of inter-turn faults in the continuous disc winding and the same methodology is extended for layer windings for a different percentage of faults in the winding. The efficacy of the methodology is checked in the layer winding.

Table 1. Capacitance ratio and resonant frequencies for continuous disc winding in the presence and absence of a grounded aluminium tank and SER

Resonant frequency Hz	Winding with the grounded tank, grounded inner core, SER on top of the winding f1 [Hz]	Winding with the grounded inner core, SER on top of the winding (grounded tank is excluded) f2 [Hz]	$\frac{C_2}{C_1}=\left(\frac{f_1}{f_2}\right)^2$
f_{r1} (anti-resonance)	794329	758578	1.096
f_{r2} (resonance)	1258930	1230270	1.047

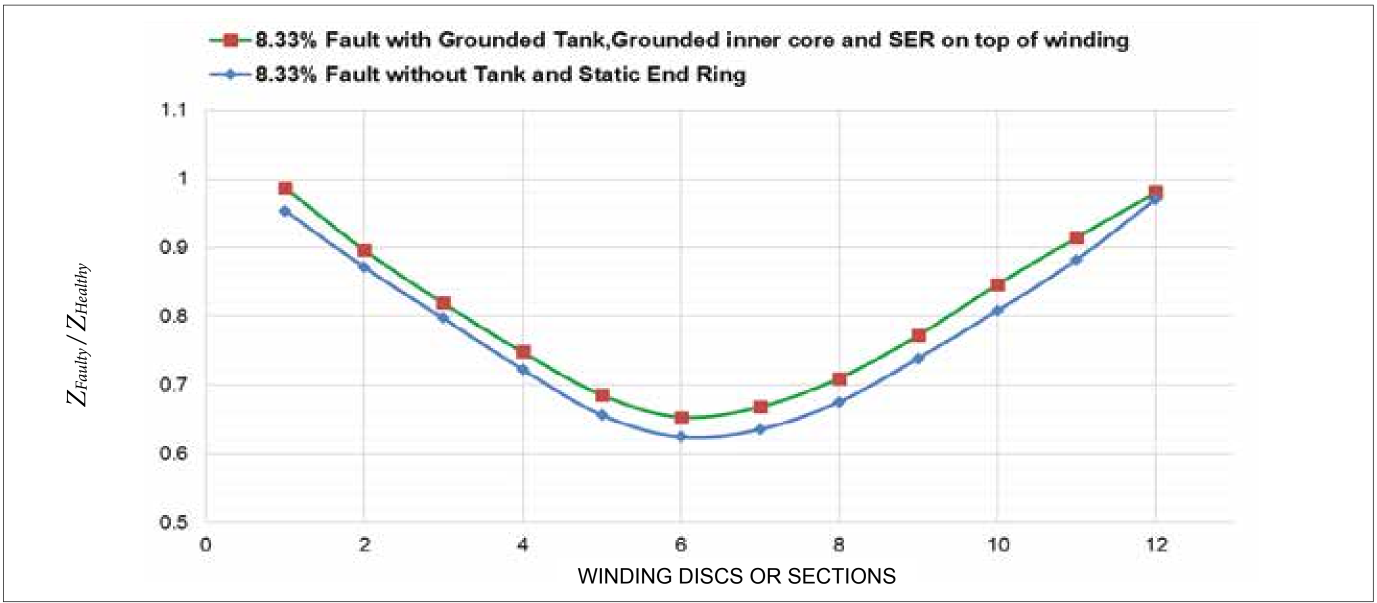

Figure 8. Fault factor vs winding disc or sections for 8.33 % inter-turn fault in continuous disc winding in the presence and absence of SER and tank

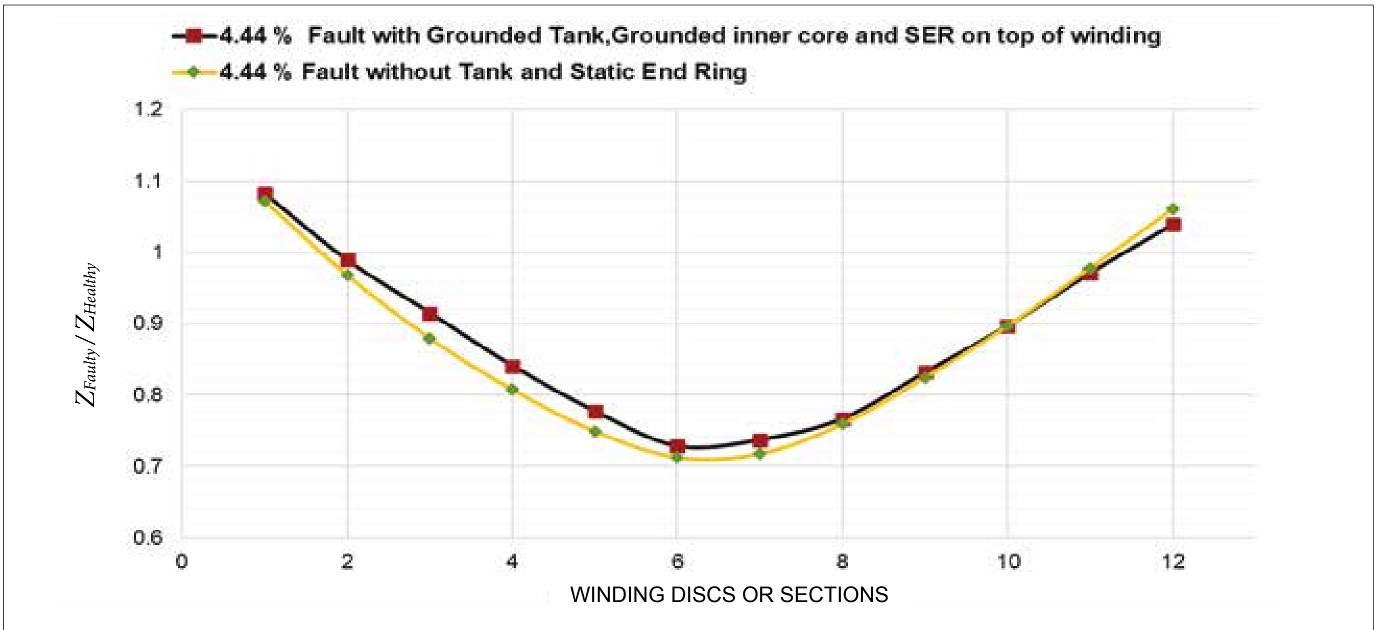

Figure 9. Fault factor vs winding disc or sections for 4.44 % inter-turn fault in continuous disc winding in the presence and absence of SER and tank

To improve the transient voltage distribution along the winding, it is necessary to make the initial voltage distribution constant (α) as low as possible; one way of accomplishing this is to increase the series capacitance by providing SER at the line terminal of the transformer winding

- From the fault factor characteristics, it is inferred that the characteristics move downwards as the percentage of inter-turn faults increases.
- An effect of the SER and tank on the detection of fault is introduced and the fault factor characteristics are obtained in the presence and absence of a SER and grounded tank.
- The absolute difference between the fault factor characteristics in the presence and absence of the SER and tank is around 0.013 for different percentage of faults.

Efficacy of the developed methodology is validated under practical cases which involve the SER, grounded inner core and grounded tank.

Frequency response analysis of a healthy winding and faulty winding at first resonance frequency is required to detect the inter-turn fault in the winding by measuring impedance over the wide frequency range. Also, the presence of SER, grounded tank housing and grounded inner core is included in the measurement to check

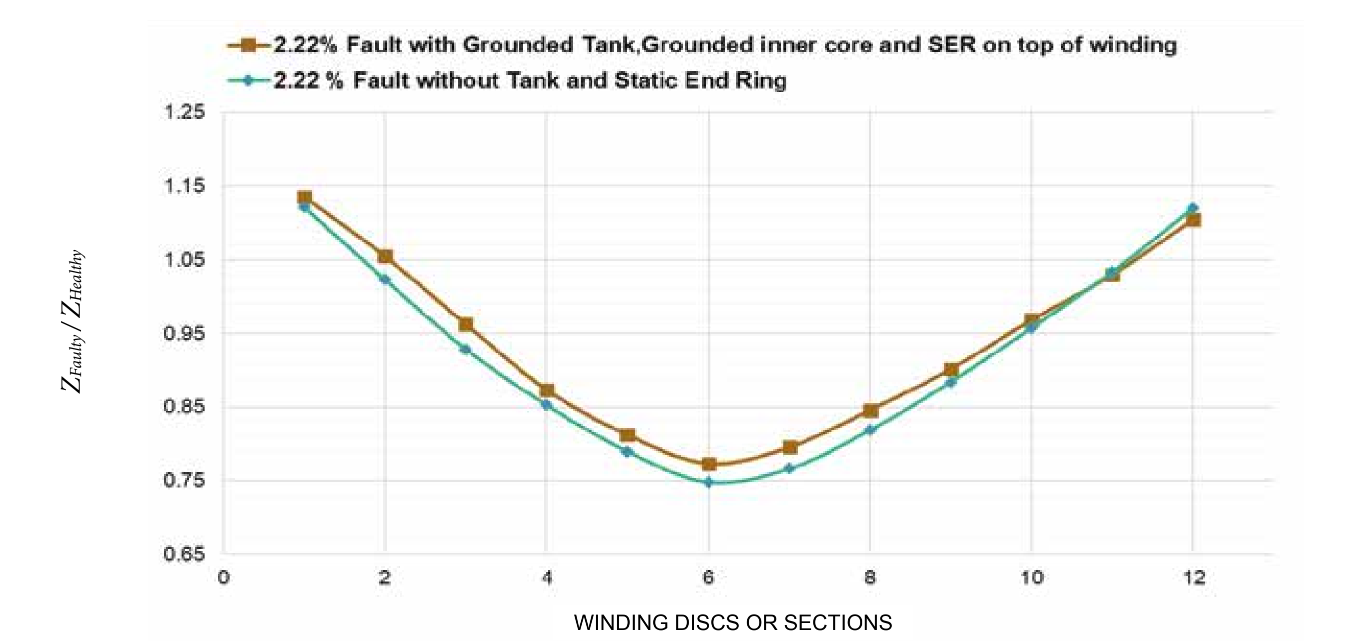

Figure 10. Fault factor vs winding disc or sections for 2.22 % inter-turn fault in continuous disc winding in the presence and absence of SER and tank

the influence of the winding distributed parameters on the detection of the fault. The corresponding flow chart for detection of fault is shown in Fig. 11.

Conclusion

The methods for the detection of the inter-turn fault in a continuous disc winding and layer windings are developed by using sweep frequency response analysis through the transformer winding circuit modelling and impedance mea-

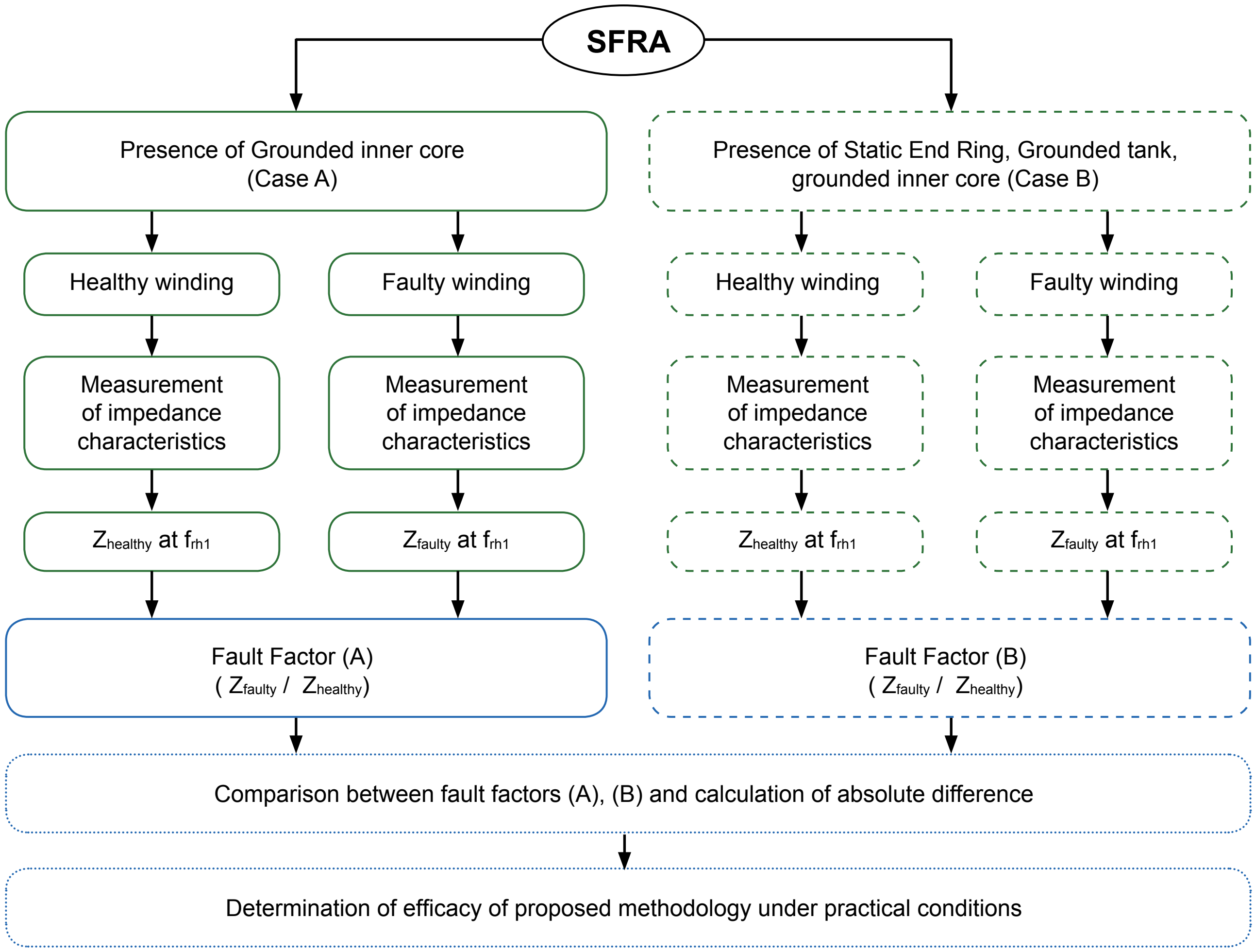

Figure 11. Flow chart for detection of a fault in the presence and absence of grounded tank grounded inner core and SER

Efficacy of the SFRA methodology is validated under practical cases which involve the SER, grounded inner core and grounded tank for different types of transformer windings

surement over a wide frequency range.

The proposed methodology provides a better insight into the detection of the fault in the winding through fault factor characteristics. Also, the effect of the grounded inner core, grounded tank and SER on top of the winding is included in the existing measurement setup to check the influence of the winding distributed parameters, such as shunt and series capacitances, on the detection of the fault.

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