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

Detection of winding inter-turn faults

Detection based on frequency response analysis - Part II

Physical dimension data of winding has been collected and winding parameters are extracted using finite element method (FEM) before actual modelling

1. Methodology for detection of fault using SFRA - circuit modelling

During the occurrence of the fault, the resonant frequencies and impedance of the winding are subjected to change depending on the percentage and location of the fault. Equivalent circuit of continuous disc transformer winding is shown in Figure 1.

In previous works [1] an algorithm for locating inter-disc faults in 22 kV continuous disc winding has been developed, which is based on FRA for determining the extent and detection of the fault. In the present study, the similar algorithm is extended to detect the inter-turn fault in the continuous disc winding and layer windings. The impedance of the healthy $Z_{Healthy}$ winding and faulty Z_{Faulty} winding at their corresponding first resonant frequency f_{rh1} is taken as a reference point. The impedance characteristics of winding is obtained by performing FRA. The measured impedance of the winding is analysed for detecting the fault. A factor relating impedance of the healthy winding $Z_{Healthy}$ and faulty impedance Z_{Faulty} at f_{rh1} is defined as Fault Factor.

$$Fault\ Factor = \frac{Z_{Faulty}}{Z_{Healthy}} \text{ at } f_{rh1} \qquad (1.1)$$

Where:
$Z_{Healthy}$ - Impedance of healthy winding (f_{rh1} is taken as a reference point)
Z_{Faulty} - Impedance of faulty winding (occurrence of inter-turn fault)
f_{rh1} - At first resonant frequency of impedance characteristics of winding

For detecting an inter-turn fault, impedance characteristics are used by comparing the impedance magnitude in a healthy winding and when an inter-turn fault occurs. A low percentage of inter-turn fault is created in the winding such as 8.33 %, 4.44 % and 2.22 %. An inter turn fault of 8.33 % indicates 15 turns are short-circuited in a single disc, i.e. short circuit is created in the equivalent circuit of transformer winding model in Pspice circuit simulation software package.

From the simulation results, impedance of the healthy and faulty winding at the first resonant frequency of the healthy winding f_{rh1} are noted as $Z_{Healthy}$ and Z_{Faulty} respectively. The impedance magnitude of the healthy winding $Z_{Healthy}$ at first resonant frequency frh1 that is 1.4791 MHz is considered as a reference point and the impedance magnitude of the faulty winding Z_{Faulty} is compared with that of first

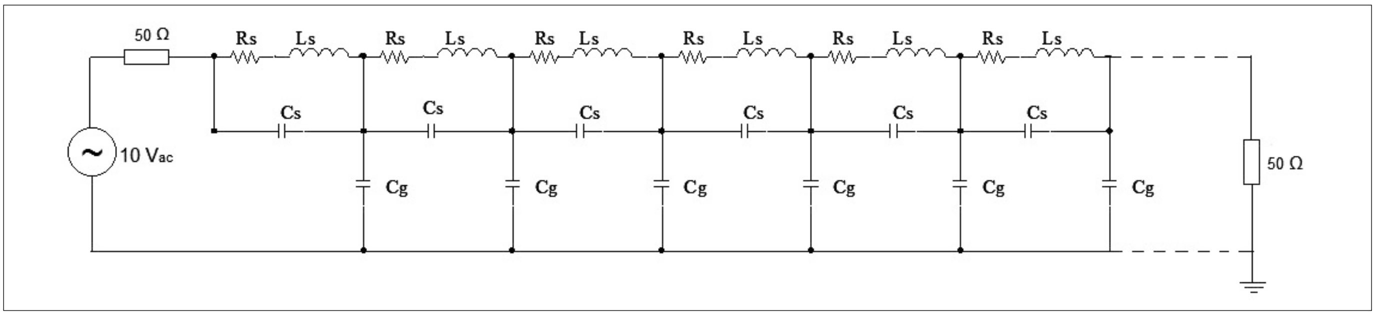

Figure 1. Equivalent circuit of transformer winding [1]

When a fault occurs, the resonant frequencies and impedance of the winding are subjected to change depending on the percentage and location of the fault

resonance frequency of healthy winding and the fault factor is calculated and this factor can be used to detect the fault.

For example, for simulation of 8.33 % fault at disc 1 in the transformer winding lumped parameter model, the first resonant frequency of healthy winding f_{rh1} is 1.4791 MHz and the corresponding impedance magnitude $Z_{Healthy}$ is 5291.234 Ω shown in Figure 2. The impedance magnitude of the faulty winding Z_{Faulty} at the corresponding f_{rh1} = 1.4791 MHz is found to be 5306.157 Ω and the fault factor is calculated.

$$Fault\ Factor = \frac{5306.157}{5291.234} \text{ at } f_{rh1} \text{ is } 1.002$$

The fault factor is calculated for different fault percentages such as 4.44 %, 2.22 % at various locations such as disc1, disc 2 up to disc 12 along the winding.

The change in fault factor with respect to location of fault is shown in Figure 3. The fault factor characteristics show exact symmetry with respect to the centre of the winding for 8.33 %, 4.44 % and 2.22 % of inter-turn faults at different locations and it shows a gradual increase in value as the location of fault moves away from the centre of the winding. The reduction in the impedance at the healthy case resonant frequency is high when the fault location is near to the centre of the winding when compared to the other cases. Fault factor values are almost the same, when the location of fault moves away from the centre of the winding to either half sections of the winding. This factor can be used to detect the inter-turn fault. Hence the proposed method is good for detection of fault with respect to the centre of the winding.

1.1. Detection of inter-turn fault in transformer winding using SFRA – circuit modelling summary

SFRA has been carried out on the continuous disc winding model using Pspice circuit simulation package. Simulation is done for healthy and different percentages of faults at different locations along the winding. The method used for detection of fault can be summarized as follows:

- The impedance of the healthy winding $Z_{Healthy}$ and impedance of the faulty winding Z_{Faulty} at first resonant frequency of the healthy winding can be taken for analysis.
- Fault factor is calculated for different percentages of inter-turn faults.
- Fault factor characteristics show exact symmetry with respect to the centre of

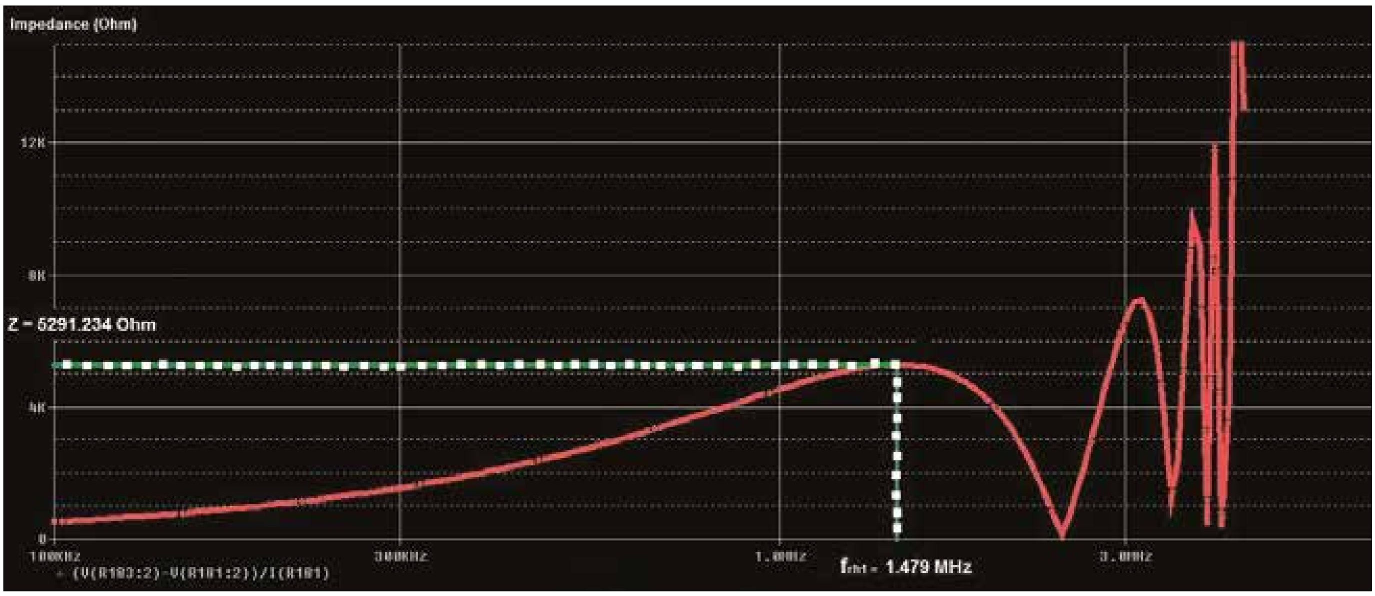

Figure 2. Simulated impedance characteristics for healthy winding

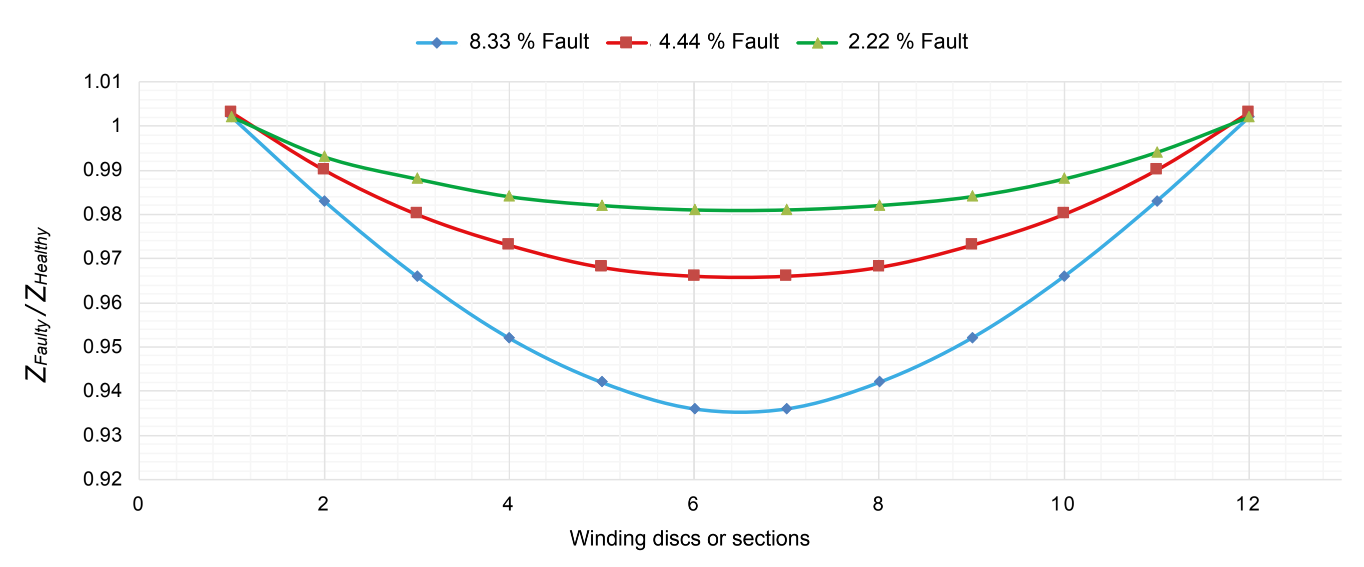

Figure 3. Fault factor vs winding sections for 8.33 %, 4.44 %, 2.22 % inter-turn fault at different locations

the winding. This factor can be used for detection of fault.

- From the fault factor characteristics it is observed that the factor values vary as the percentage and location of fault changes.
- Fault factor characteristics shift downwards as the percentage of fault in the winding increases.

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

SFRA proceeds by injecting a sinusoidal signal of constant amplitude and variable frequency into one end of a winding and measuring the response, which is also a sine wave but with different amplitude and phase, at the other end. Also, in this case, the transfer function results from a comparison of the input and output signal. Since this method measures directly in the frequency domain, no further signal processing is needed. The existing methods do not give reliable information about the status and location of the winding precisely. Geometrical changes within and between the elements of the network cause deviations in its frequency response. Differences between an FRA fingerprint and the result of an actual measurement is an indication of positional or electrical variations of the internal components [2]. Many researchers reported [3], [4, 5] that impedance, stray capacitance between winding and core or tank, series capacitance and inductance of winding is subjected to change

For detecting an inter-turn fault, impedance characteristics are used by comparing the impedance magnitude in a healthy winding and when an inter-turn fault occurs

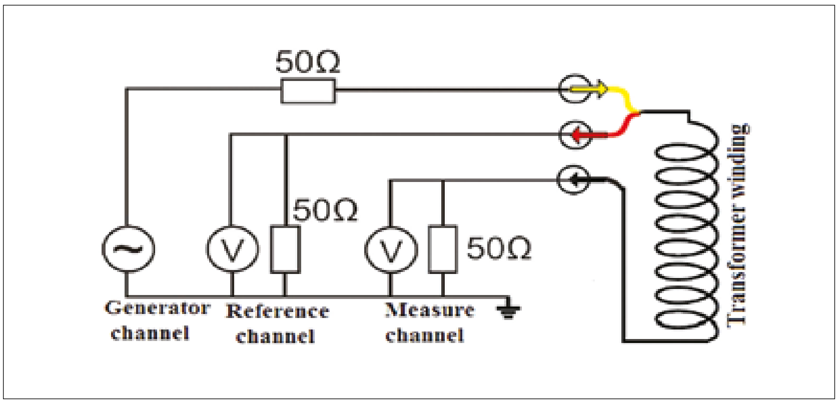

Figure 4. Experimental setup for FRA [6]

Figure 5. Continuous disc winding

The fault factor characteristics show exact symmetry with respect to the centre of the winding and it shows a gradual increase in value as the location of fault moves away from the centre of the winding

during the occurrence of a fault depending on the type, location, and severity of the fault.

FRA measurement is made by injecting low voltage signal into the top of the selected winding structure and acquiring a voltage signal appearing at the bottom section of the winding structure and calculating transfer function. The voltage measured at the input terminal (V_{in}) is used as a reference for the FRA. A second parameter (response signal) is usually a voltage (V_{out}) taken across impedance connected to the transformer's second terminal with reference to the tank.

The FRA magnitude is the signal amplitude relationship between V_{in} and V_{out} signals and is represented as decibels:

$$Magnitude\ (dB) = 20 \cdot \log_{10}\left(\frac{V_{out}}{V_{in}}\right) \quad (2.1)$$

Hence the impedance characteristics of the winding are analysed through frequency response analysis. An attempt is made to detect the inter-turn faults in transformer winding by observing the changes in impedance characteristics.

Figure 4 shows the experimental setup for frequency response analysis. SFRA has been carried out on 12 discs continuous winding from 10 Hz to 25 MHz.

2.1. Detection of inter-turn fault in transformer winding using SFRA – measurement results

Figure 6 shows schematic diagram of continuous disc winding. Each disc consists of 15 turns and total number of turns in the winding is 180.Tappings were brought out to create inter-turn short circuit fault.

2.1.1. Transformer winding - percentage of fault calculation

$$Percentage\ of\ Fault = \frac{n}{N} \cdot 100 \quad (2.2)$$

Where:
n - Number of turns shorted per disc or section

N - Total number of discs or sections in the winding (d) * number of turns per disc or section in the winding (t)

For instance, 8.33 %, 4.44 % of inter-turn fault is created in the winding by shorting 15 turns per disc and 8 turns in a single disc respectively.

For continuous 12 discs winding having 15 turns per disc,

$$4.44\ \%\ inter\text{-}turn\ fault = \frac{8}{12 \cdot 15} \cdot 100\ \%$$

Frequency response of the winding changes depends on the location and severity of the fault in the winding. During the occurrence of fault, the distributed parameters of the winding are subjected to change. Hence further analysis on frequency response of the winding has to be done to detect the fault precisely. Figure 7 shows the impedance characteristics for healthy winding and inter turn faults at different locations in the winding. It can be observed that the impedance of the winding is comparatively small at low frequencies and it increases gradually as the frequency is increased. Multiple resonances can be observed in the measured impedance characteristics because the frequency response trace is completely dependent on winding inductance as well as on the series and shunt capacitances and also, each and every transformer winding type has its own α (voltage distribution parameter) value which is the ratio of shunt and series capacitances of winding. Numerous studies have been conducted over the years to explore the methods to decrease the value of α in various types of transformer windings. This may be done either by reducing shunt capacitance or alternatively, by increasing the series capacitance. It is proven that interleaved winding shows less α compared to continuous disc winding. Significant value for shunt capacitance compared to series capacitance (huge α) will lead to maximum number of resonant frequencies. Hence frequency response trace for continuous winding demonstrates more oscillations (multiple resonant frequencies) [5].

The first resonant frequency f_{rh1} is found to be 699.842 kHz and the corresponding impedance value is 3823.4 Ω. It shows the reduction in impedance magnitude and shift in resonant frequency during the occurrence of fault. It also shows the reduction in impedance magnitude, as the location of fault changes. Thus the reduction

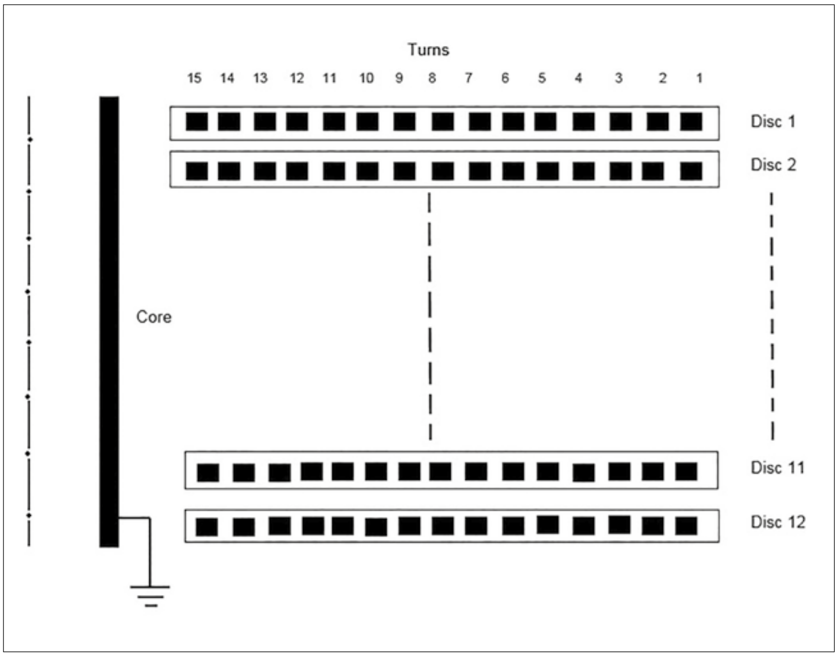

Figure 6. Schematic of continuous disc winding (side view)

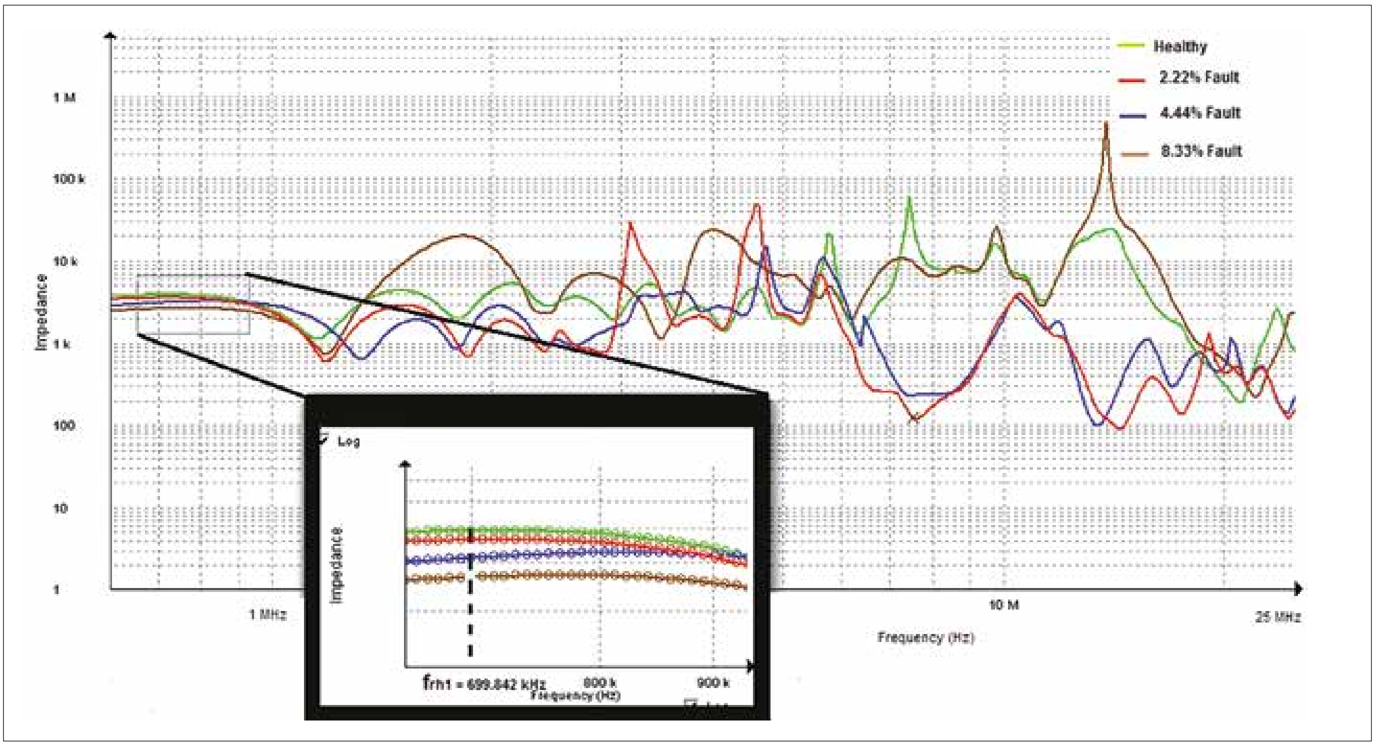

Figure 7. Impedance characteristics for healthy winding and faulty winding (8.33 %, 4.44 %, 2.22 % inter-turn faults)

in impedance magnitude at the first resonant frequency can be analysed further to detect the fault.

The goal is to detect the inter-turn faults in transformer winding by observing the changes in impedance characteristics

Figure 8 shows fault factor versus winding sections for 8.33 %, 4.44 %, 2.22 % faults at different locations along the winding. The change in the fault factor values with respect to the location of fault can be further studied for detection of inter-turn fault. It is clear from the plot that, when the location of fault changes, fault factor changes. But it can be observed that the values are symmetrical with respect to the centre of the winding. The values of the parameter are almost the same when the location of fault

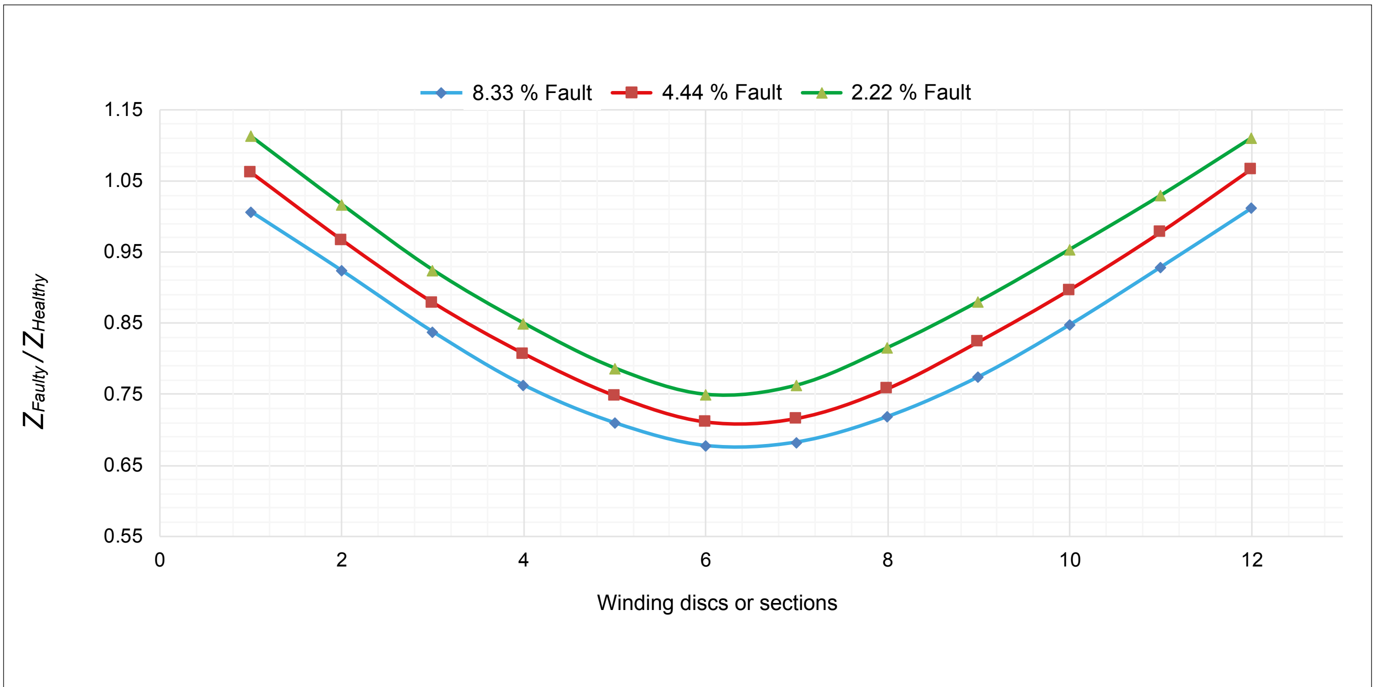

Figure 8. Fault factor vs winding sections for 8.33 %, 4.44 %, 2.22 % inter-turn fault at different locations

moves away from the centre of the winding. It is inferred from the fault factor characteristics that as the curve shifts downwards as the percentage of inter-turn fault increases.

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Detection of inter-turn fault is critical since its effect is not easily comprehendible at lower magnitude in the signatures of terminal voltage and current

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