Inter Turn Fault Location in
Transformer Winding Using SFRA

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Abstract : *Inter turn short circuit faults are the leading cause of power transformer failures. These failures usually develop into more serious faults that would result in irreversible damage to the transformer, unexpected outages and the consequential costs. This contribution is aimed at locating inter turn faults using the impedance characteristics of the transformer winding. In this work, various percentages of inter turn faults at different locations of the winding are created and the frequency response characteristics of a continuous disc winding are analyzed to predict the location of fault using Sweep Frequency Response Analyzer.*

Key words : *Transformer winding, inter turn faults, SFRA and fault location.*

1.Introduction

Power Transformer plays a very important role in a power system. Damages to power transformer are unwelcome since the continuity in power delivery may be seriously disrupted. The insulation is mainly affected due to the over voltages. In view of increasing demand for reliable and high quality energy supply, power sectors are more interested in avoiding transformer failures. Arising primarily from turn insulation degradation, inter-turn winding faults are one of the leading root causes of failures in power transformers. Among the survey of various faults about 19% of faults that occur in transformers are winding faults. These faults create local hot spots in the area which leads to the breakdown [1]. Among the detection of various faults, detection of inter-turn fault is critical since its effect is not easily comprehendible at lower magnitude in the signature of terminal voltage and current.

Frequency Response Analysis (FRA) as one of the well-recognized methods for diagnosis of power transformers is based on the fact that every transformer winding has a unique signature of its transfer function which is sensitive to change in the parameters of the winding, namely resistance, inductance and capacitance. Any geometrical or electrical changes within the transformer due to internal faults, cause a change in the transfer function of the winding and consequently a modification of its frequency response [2-3].

In general, various parameters are used for fault location in the transformer winding such as fault current in the faulted loop, neutral current, transfer function, impedance and terminal voltage and current[4-13]. In [14], a generalized algorithm using the Fault Factor characteristics and employing the hyperbolic model is developed for locating inter disc faults in continuous disc transformer winding based on the impedance characteristics of the winding.

In this paper, an attempt is made to extend the developed methodology to predict the location of inter tun fault in transformer winding using sweep frequency response analysis.

2.Inter Disc Fault Location –Hyperbolic Model

In [14], A simple algorithm with a new diagnostic parameter is developed for the identification of location of inter disc fault in a 22 kV continuous disc winding using Sweep Frequency Response Analysis (SFRA). The percentage of fault is determined from the reduction in impedance at 0.1 Hz where, stray capacitive and skin effects are negligible.The change in the impedance at the first resonant frequency of the healthy winding for various faults, in terms of the defined Fault Factor is used to locate the faults with respect to the center of the winding. The percentage faults upto $(1/N)*100$, where N is the number of discs, can be located using the proposed methodology.

To locate, whether the fault has occurred in the upper or lower sections of the winding, two methods namely Sweep Frequency Response$_{50\%}$(SFR$_{50\%}$) and ground capacitive current methods are proposed. The methodology is employed for onsite transformer winding if the access to the centre tapping is available using SFR$_{50\%}$.Under the situations, where the access to mid point of the windings is difficult, the location of fault can be identified using ground capacitive current analysis.

A hyperbolic model is proposed to predict the fault factor characteristics and to locate the inter disc fault by measurement using a 22 kV continuous disc winding. As the FF characteristics are hyperbolic in nature, the proposed methodology employs the hyperbolic model, requiring only two terminal measurements to predict the exact fault location for different percentage of faults.The

values of the hyperbolic parameters are interpolated to predict the location for other percentage of faults.[14]

3. Frequency Response Analysis

3.1 Experimental

Short circuit fault between two adjacent discs and two adjacent conductors in the disc is given as inter disc and inter turn faults respectively. In the transformer winding, the percentage fault greater than $(1/N)*100$ where N is the number of discs is referred as inter disc fault. The percentage fault greater than $(1/(n*N))*100$ and upto $(1/N)*100$, where n is the number of turns/disc is referred as inter turn fault.

To extend the proposed methodology to locate the inter turn fault, Sweep Frequency Response (SFR) is carried out on a prototype 12 disc continuous winding which is designed specifically with facility to short inter turns. With 15 turns in each disc, the winding has a total turns of 180. The specifications of the winding are given in Table 1. Fig. 1(a) and 1(b) show the plan and elevation of the prototype 12 disc continuous winding respectively.

Table 1

Specifications of 12 disc continuous winding

Turns per disc	15
Number of discs	12
Size of conductor	10*3
Average turn length	136
Distance between discs	30
Height of section axial	480
Coil diameter (Outer)	154
Coil diameter (Inner)	85
Core thickness	2
All dimensions are in mm	

Fig. 1(a) 12 disc continuous winding (Plan)   Fig. 1(b) 12 disc continuous winding (Elevation)

Impedance characteristics of the winding are measured using Sweep Frequency Response Analyser (FRAX 101, Megger Make). The instrument has a sweep frequency voltage source of 10 V peak-to-peak in the frequency range of 0.1Hz to 25MHz. The FRAX "Generator channel" generates a sinusoidal voltage and measures the voltages, amplitude and phase, on two channels called "Reference channel" and "Measure channel"[15].

The recommendations for standardizations of SFRA practices have to be followed for precise, repeatable and consistent measurement [16-17]. The experimental set up to measure the SFR is shown in Fig. 2. The SFR of the winding are measured under healthy and faulty conditions.
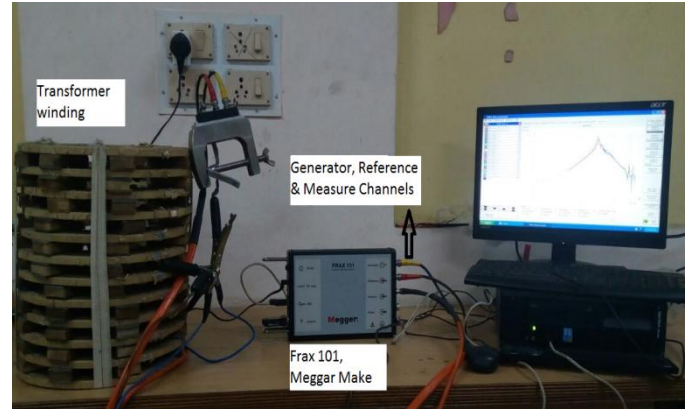

Fig. 2. Experimental set up for SFRA on 12 disc continous transformer winding

3.2 Inter disc faults

SFR of the healthy winding is measured and shown in Fig. 3. The first resonant frequency of the healthy winding (f_{rh1}) is 616.595 kHz and the impedance at f_{rh1} is 4016.1 Ω.
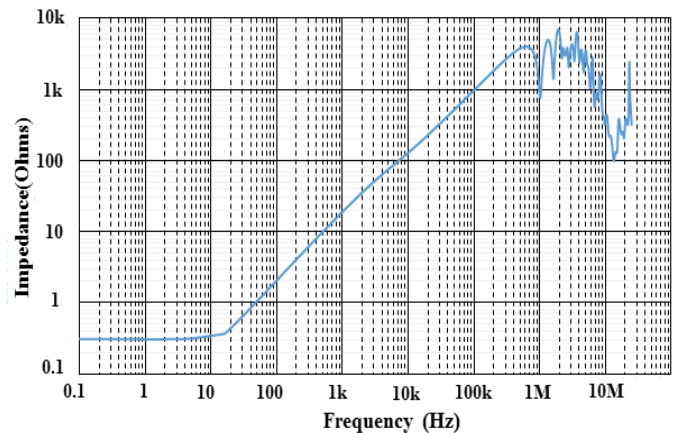

Fig. 3. SFR of the healthy continuous disc winding

Inter disc faults of various percentages at different locations along the winding are created purposely by shorting the discs at predetermined locations. The inter disc faults containing 16.66% of winding's turns are created by shorting 2 discs along the length of the 12-disc winding and the fault is represented as a pair of numbers(%fault , winding section). For instance (16.66,

1) represents 16.66% fault in the first 16.66% section (comprising of top 2 discs) from the top of the winding. Single disc faults of 8.33% of faults are effected by shorting turn 1 to turn 15 of each disc.

When an impulse voltage impinges on the transformer winding, the winding behaviour can be divided into three stages viz, initial, intermediate and final voltage distribution. During the initial period of the impulse, due to steep front, the voltage has very high frequency components. During this period, the inductive reactance is very high compared to the very low capacitive reactance and the winding behaves as a pure capacitive network.　During the intermediate period, interaction of the electrical and magnetic energies stored in the capacitance and inductance is developed, giving rise to an oscillatory period and hence the winding behaves as a combination of resistive, inductive and capacitive circuit. During final stage, when the voltage is almost constant with very low frequency components, the winding behaves as a series resistive and inductive RL circuit.Hence, the percentage of fault in the winding is determined from the percentage reduction in impedance at very low frequency (0.1Hz) where, stray capacitive and skin effects are negligible[14].

$$\text{Reduction in impedance} = \frac{(Z_{healthy} - Z_{faulty})}{Z_{healthy}} \quad (1)$$

Where　　　$Z_{healthy}$ = Impedance of healthy winding
　　　　　　Z_{faulty} = Impedance of faulty winding

SFR are measured for 16.66% and 8.33% of faults at various sections along the winding. The percentage reduction in impedance (average of impedances measured at different sections) with respect to the healthy winding at 0.1 Hz is 7.8, 15.9 for 8.33%, 16.66% faults respectively.The deviation from the actual percentage of fault is due to the effect the tappings and connection leads[14].Hence, from the reduction of impedance at 0.1Hz, the percentage of fault occurred in the transformer winding can be determined.

Once the percentage of fault in a winding is known, further analysis is carried out to determine the location of the fault. A factor relating $Z_{healthy}$ and Z_{faulty} at f_{rh1} is defined as **Fault Factor**[14] where

$$\text{Fault Factor(FF)} = \frac{Z_{faulty}}{Z_{healthy}} \text{ at } f_{rh1} \quad (2)$$

The FF for 8.33% and 16.66% faults at different sections of the winding is calculated. Fig. 4 shows FF against Disc Number for 8.33% and 16.66% faults, is symmetrical with respect to the centre of the winding and

are found to be hyperbolic in nature. Thus, the location of fault from the centre of the winding can be identified.

To locate, whether the fault has occurred in the upper or lower sections of the winding, $SFR_{50\%}$ method is used as the methodology is employed for transformer which has access to the centre tapping of the winding. For x% faults occurring in the lower half of the winding, the reduction of lower half impedance of the winding is observed to be almost 2x%. Thus, the reduction of lower half impedance at 0.1 Hz is negligible and almost 2x% for x% of fault in the upper and lower section of the winding respectively. Hence, the fault location can be identified whether in the upper/lower section of the winding using $SFR_{50\%}$.
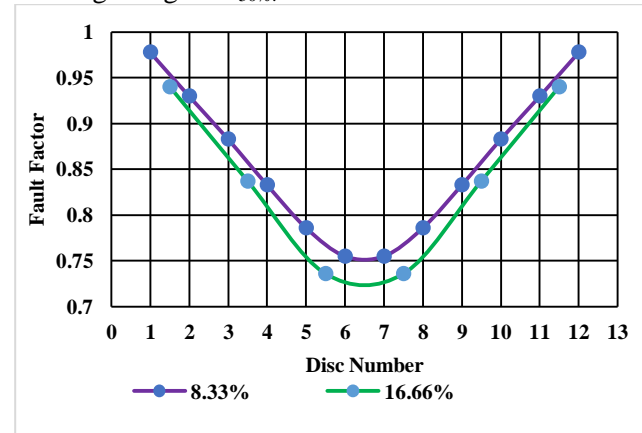

Fig. 4. FF characteristics for different percentage of inter disc faults along the continuous disc winding

3.3 Inter turn faults

The developed methodology to locate the inter disc faults [14] is extended to locate the inter turn fault in the 12 disc continuous winding. As the shorting of turns is difficult near the centre of the discs, inter turn faults are created only near the tank (Region A) and the core (Region B).In order to extend the methodology for the location of inter turn faults, single inter turn faults (1/(180) = 0.55% fault) are created near Region A and Region B as shown in Fig.5.

SFR are measured for 0.55% faults at Region A and Region B along the winding and FF are tabulated (Table 2). In the Table 2, sequence of numerals given in brackets in the Z_{faulty} of Region A and B denote the connection scheme of the continuous disc winding. In Fig. 6, FF for 0.55% faults along the winding in Region A and B are represented as dotted line. The value of FF for 0.55% fault at various locations along the winding is obtained by calculating the mean of the FF at the corresponding Region A and B. In Fig.6 , the calculated mean FF characteristics for 0.55% faults along the

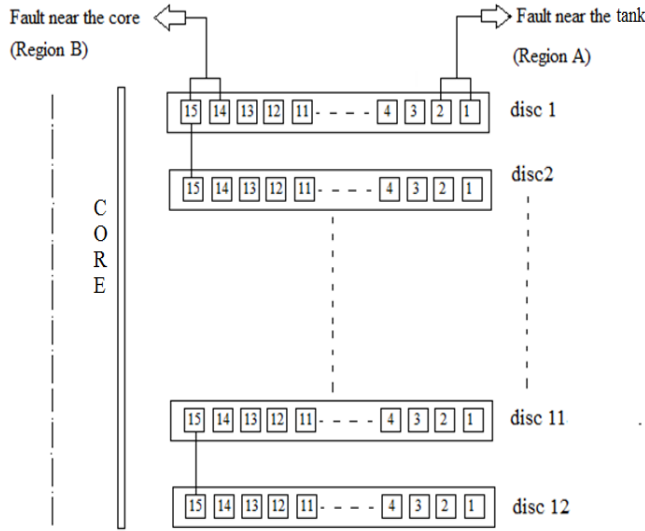winding which is hyperbolic in nature is shown as solid line.

Fig. 5. Single inter turn faults in the continuous disc winding

FF of the starting turn of each disc is higher than the end turn of the respective disc. A gradual decrease in the FF is observed from the start of the disc 1 to end of the disc 6 depending on the connection scheme of the winding. A gradual increase in the FF is observed from the start of 7th disc to end of 12th disc. It is also observed from Table 2 that the percentage difference of the FF at Region A and Region B is 2.3% at the topmost and the bottommost discs of the winding whereas it is only 0.1% at the center section of the winding discs.

Table 2
Z_{faulty} and FF for single turn faults at Region A and B along the continuous disc winding

| Disc Number	Region A		Region B		Mean FF
	Z_{faulty} (Ω)	Fault Factor	Z_{faulty} (Ω)	Fault Factor	
1	(1) 4059	1.011	(2) 3971.6	0.989	1.001
2	(4) 3942.7	0.982	(3) 3967.6	0.988	0.985
3	(5) 3877.7	0.966	(6) 3856.8	0.960	0.963
4	(8) 3746.5	0.933	(7) 3772.9	0.939	0.936
5	(9) 3599.1	0.897	(10) 3594.5	0.895	0.896
6	(12) 3459.9	0.861	(11) 3465.5	0.863	0.862
7	(13) 3460.2	0.862	(14) 3464.5	0.863	0.862
8	(16) 3605.1	0.898	(15) 3595.7	0.895	0.896
9	(17) 3751.7	0.934	(18) 3771.5	0.939	0.937
10	(20) 3882.8	0.967	(19) 3862.4	0.962	0.964
11	(21) 3943.9	0.982	(22) 3960	0.986	0.984
12	(24) 4074.8	1.015	(23) 3980	0.991	1.003
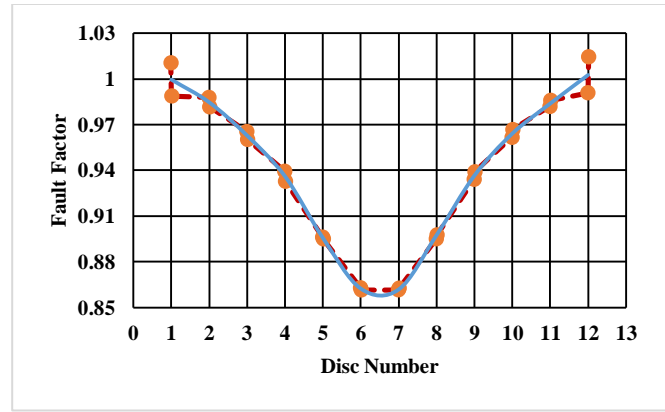
Fig. 6. FF characteristics for single inter turn faults (0.55%) at Region A and B along the continuous disc winding

Similarly, SFR are measured for 4.44% inter turn faults by shorting 1-8 turns at Region A and by shorting 8-15 turns at Region B at each disc in the winding. The obtained FF characteristics for 4.44% faults at Region A and B at different locations along the continuous disc winding are found to be hyperbolic in nature and shown in Fig. 7. It is evident from Fig. 7 that the percentage difference of the FF at Region A and B is more at the topmost and the bottommost discs when compared to that of the discs at the center for any percentage of faults occurring in the continuous disc winding.
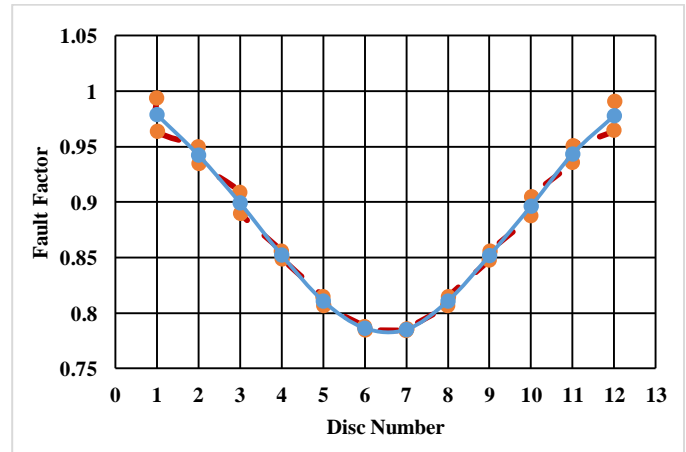

Fig. 7. FF characteristics for 4.44% inter turn faults at Region A and B along the continuous disc winding

The FF characteristics for inter disc and inter turn faults along the winding are shown in Fig. 8. It is observed from Fig. 7, that there is an upward shift in the FF characteristics as the percentage of fault decreases i.e. from inter disc to inter turn faults. In general, the percentage faults upto $(1/(n*N))*100$, where N is the number of discs and n is the number of turns/disc, can be located using the methodology.
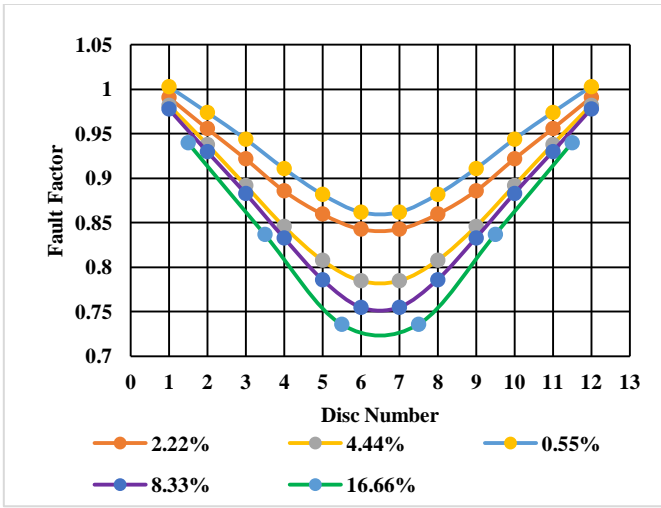
Fig. 8. FF characteristics for different percentage of inter disc and inter turn faults along the continuous disc winding

The FF characteristics fit in hyperbolic model perfectly. A hyperbola centred at (h,k) has the equation

$$\frac{(x-h)^2}{a^2} - \frac{(y-k)^2}{b^2} = 1 \qquad (3)$$

In the Equation, (h,k), x and y represents the physical centre of the winding (6.5,0), disc number and corresponding FF respectively. Hyperbolic parameters 'a_{hm}' and 'b_{hm}' are obtained for different percentage of faults obtained using hyperbolic model with only two reference values as shown in Fig. 9.
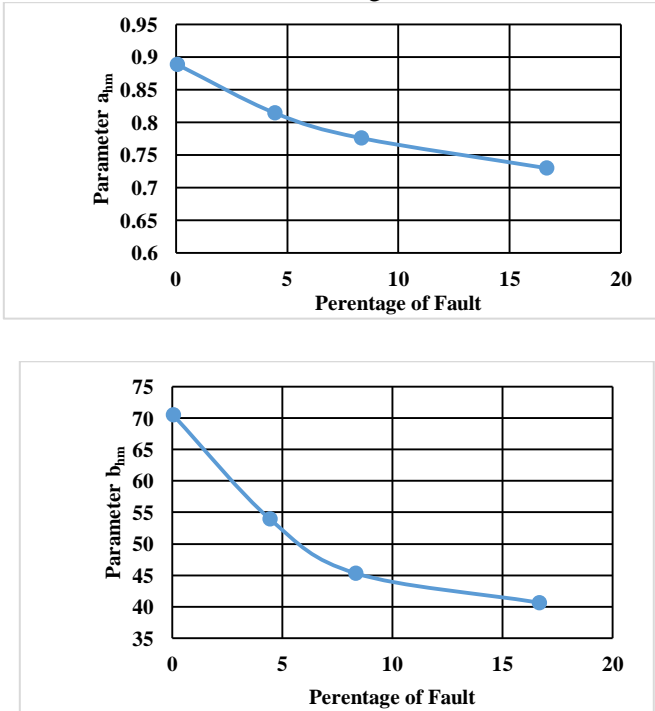
Fig. 9. Hyperbolic parameters for different percentages of faults in the continuous disc winding

Using the above discussed methodology, the disc with even single inter turn fault can be identified. Further to locate the position of the fault in the faulted disc, an attempt is made to check the FF of the inter turn fault across a single disc. SFR are measured for single inter turn faults by shorting consecutive turns (i.e 1-2, 2-3, 3-4...) along the first disc and FF is plotted as shown in Fig. 10(a). FF of 0.55% fault shows monotonical reduction in value from Region A to Region B of the disc 1. Using curve fitting technique, it is observed that it fits with the equation of a straight line with the deviation less than 0.06%. As the variation of FF across a disc is almost linear, the FF measured at the regions A and B alone can be used to define a straight line and locate the exact location of fault.
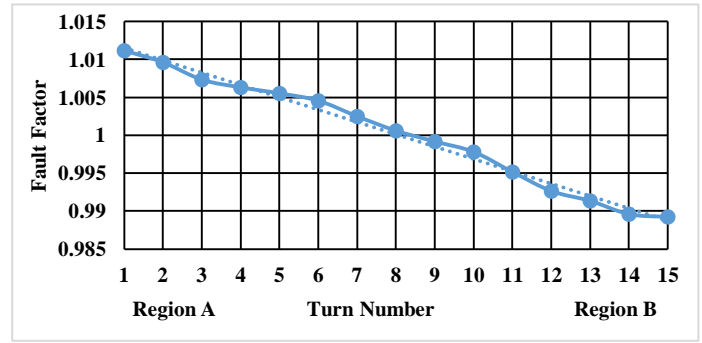

Fig. 10(a) FF characteristics for 0.55% inter turn faults along the disc 1

Similarly, SFR are measured for 4.44% and 2.22% inter turn faults by shorting eight turns (i.e 1-8, 2-9, 3-10…) and four consecutive turns (i.e 1-4, 2-5, 3-6...) along the first disc respectively and shown in Fig. 10(b). It is observed that the corresponding FF also shows the linear reduction in value from Region A to Region B along the first disc with the maximum error less than 0.05%.
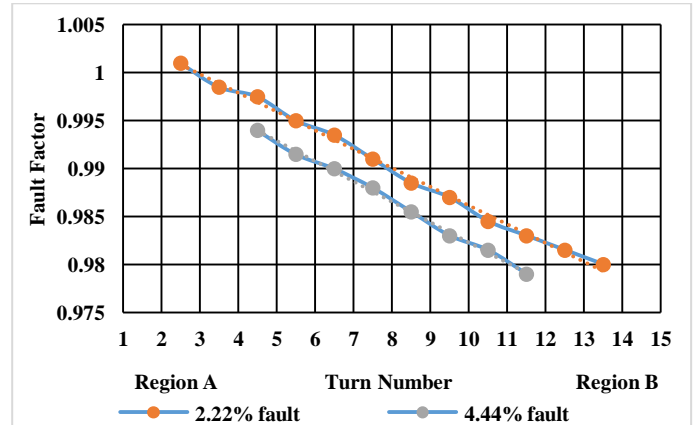

Fig. 10(b) FF characteristics for inter turn faults of different percentages along the disc 1

4. Validation

To check the validity of the proposed methodology, an inter turn fault is created by shorting 4-7 turns of Disc 4 of the continuous disc winding. To start with, SFR under healthy and faulty conditions of winding are measured and shown in Fig. 11(a).

- Percentage of fault: The impedance for healthy and faulty winding at 0.1 Hz are measured to be 0.3096 Ω and 0.3031 Ω respectively. The percentage reduction in impedance is calculated as 2.1% (Fig. 11(b)). The inter turn short of 3 turns and 4 turns correspond to 1.66% and 2.22% inter turn fault in the winding respectively. Hence, actual percentage of fault occurred in the winding should be 2.22%.
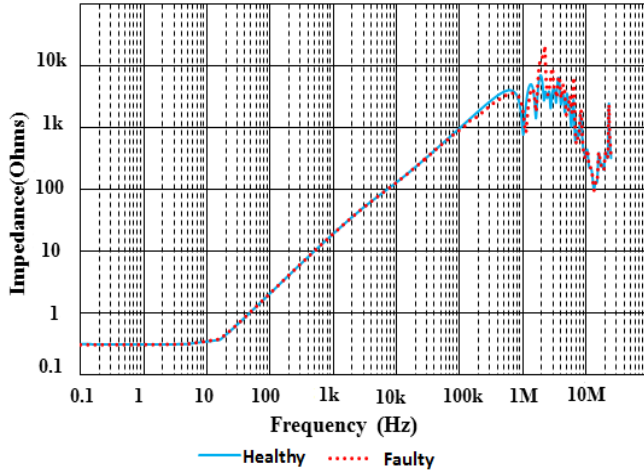

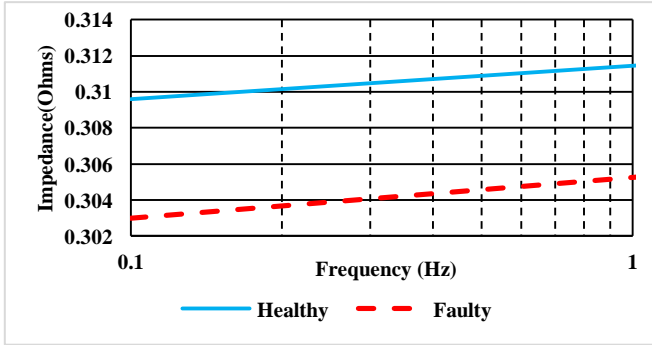Fig. 11(a) SFR of the healthy and faulty winding

Fig. 11(b) SFR of the healthy and faulty winding at low frequency

- Fault Factor: It is observed from Fig. 11(c), that the impedance of the healthy and faulty winding is found to be 4016.1 Ω and 3542.2 Ω at f_{rh1} (616.595 kHz) respectively and the corresponding value of FF is 0.881.
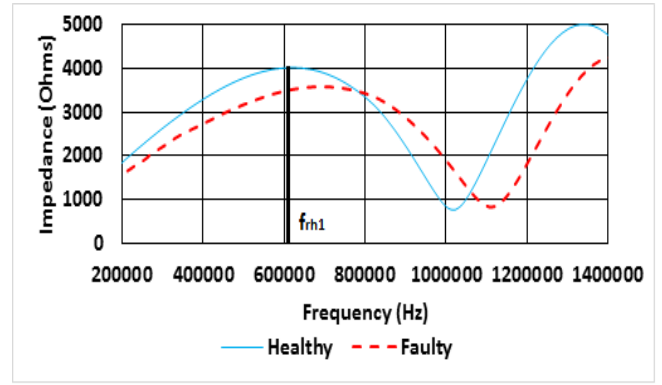

Fig. 11(c) SFR of the healthy and faulty winding at frh1

- Prediction of FF Characteristic for 2.22% fault: In order to determine the location of fault, the hyperbolic parameters 'a_{hm}' and 'b_{hm}' are extracted for 2.22% from Fig. 6.12 (enlarged version of Fig. 9) and found as 0.851 and 62.1.

- Location of fault: The corresponding FF characteristic is predicted using Equation (3) and shown in Fig. 13. The measured FF of the faulty winding (0.881) is closer to disc 4 and disc 9. Hence, it is evident that the fault location is either in disc 4 or disc 9.
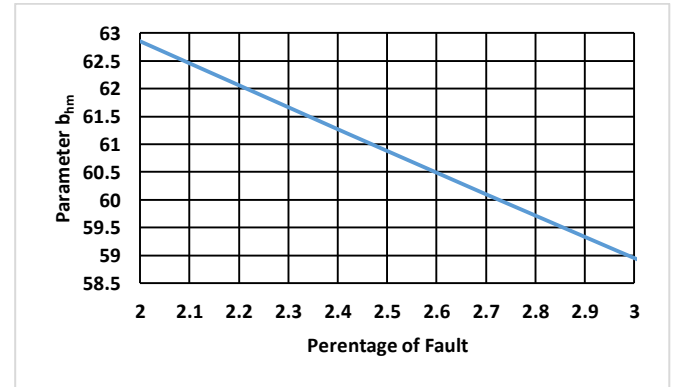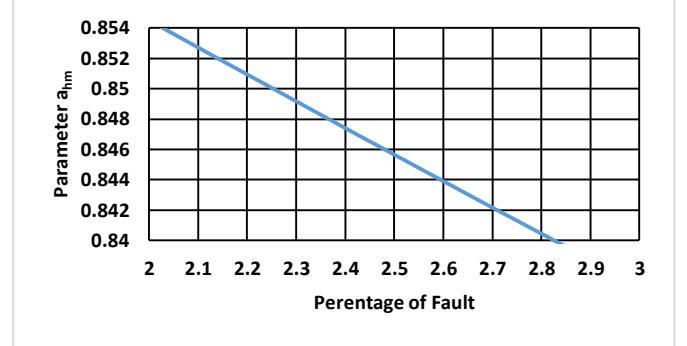

Fig. 12. Hyperbolic parameters for different percentages of faults in the continuous disc winding

• Location of faulted disc (Upper/Lower): The impedance at 0.1 Hz are measured to be 0.1529 and 0.1526 from the SFR$_{50\%}$ of the healthy and faulty winding respectively (Fig.14). It is observed that the percentage reduction of the lower half impedance at 0.1 Hz is almost negligible. Hence, the fault location is in the upper sections of the winding i.e disc 4.
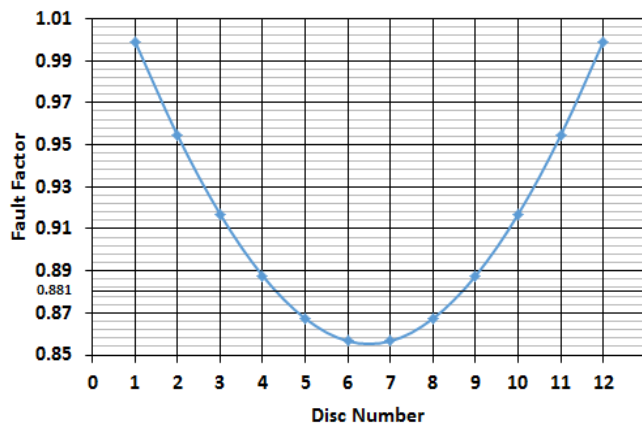

Fig. 13. FF characteristic using hyperbolic model for 2.1% fault

• Location of faulted turns: The value of FF (0.881) is lesser than the mean FF value (0.887) obtained by hyperbolic model at disc 4 from Fig. 15(enlarged version of Fig. 6.13). Based on the connection scheme (Table 1), for the inter turn fault in disc 4 , value of FF for faults near to Region A is lesser to mean FF and near to Region B is greater to mean FF. Hence, as the FF value is lesser than the mean FF, it can be concluded that the fault location is near to Region A.
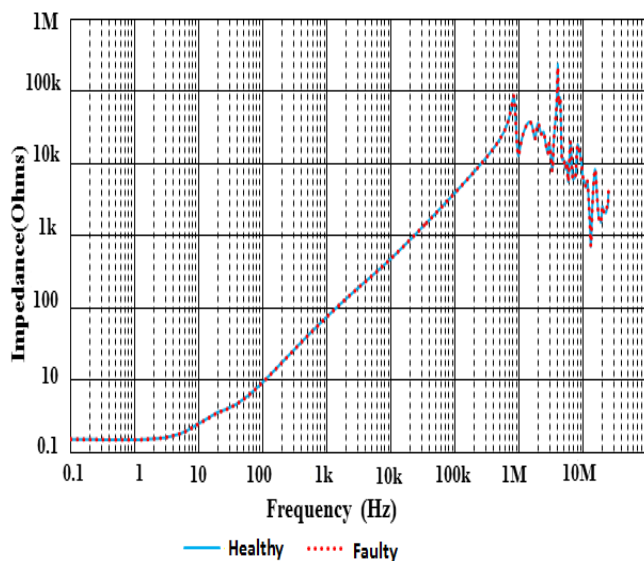

Fig. 14. SFR$_{50\%}$ of the healthy and faulty winding

Results:
Actual Percentage of fault : 2.22% (short of 4 turns)
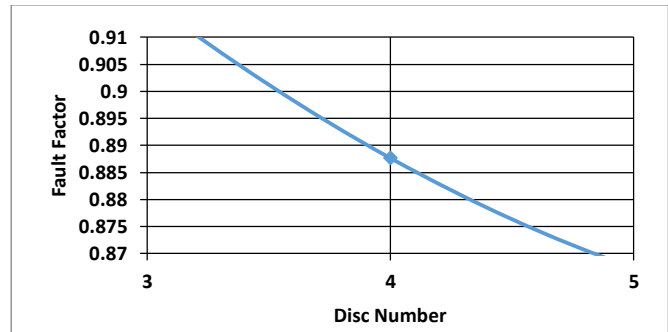Location of fault : Near the tank (Region A) of disc 4

Fig. 15. FF characteristic using hyperbolic model for 2.1% fault near disc 4

The detected percentage and location of fault using the developed methodology agree well with the actual fault which has been created between the turns in the winding. Hence, the proposed methodology is validated for the inter turn fault detection and location in the transformer winding.

The value of FF shows linear monotonical reduction in value from Region A to B or vice versa in a disc, in the continuous disc winding based on the connection scheme. The values of the hyperbolic parameters are interpolated to predict the FF characteristics using the hyperbolic model and thereby the location of any percentage of inter turn faults whether it has occurred either near to the tank or core is identified with good accuracy.

5.Conclusion

Detection and localization of winding faults is essential for preventing further damages to the transformer. The developed methodology in [14], is extended to determine location of inter turn fault and verified using a continuous disc winding. The percentage faults upto (1/(n*N))*100, where N is the number of discs and n is the number of turns/disc, can be located using the proposed methodology.

The developed algorithm is checked upto inter turn faults in a continuous disc winding. The percentage and location of fault are detected with good accuracy using the measured SFR and SFR$_{50\%}$ of the healthy and faulty winding. The methodology requires the impedance characteristics only up to the first resonant frequency for the location of faults. Thus, the transformer designers can obtain the hyperbolic models for any percentage of faults using circuit simulation package with only low frequency equivalent circuit model at the design stage itself which will be useful for locating the fault.

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