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Identifying and Locating Connection Fault of Layer Winding Turn in Distribution Transformer

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Abstract *– Transformers are considered as the most important and expensive distribution and transfer networks of electrical energy. Among different fault identifying in transformers, identifying winding fault is not easily recognizable because of lower domain effect in terminal voltages and currents. In this article, frequency response analysis method is used as an efficient method to recognize turn's connection fault. By comparing frequency response in fault and intact conditions, fault recognizing in winding becomes possible. In order to determine frequency response, the described winding model is used. Analyzing the model is done by MATLAB software. The accuracy of this model is very dependent on determining its parameters. In order to exact calculation of parameters of described winding model, Finite Element Method based on winding design information is used and in order to increase accuracy, parameter dependency to frequency is considered. Finally, the effect of turn's connection fault and its location on layer winding of a distribution transformer is evaluated.*

Keywords*: Frequency Response, Finite Element Method, Turn's Connection Fault, Locating*

INTRODUCTION

Power transformers are considered as the most important and expensive elements of distribution and transfer networks of electrical energy and hence by the increase of demand for intact and safe electrical energy, avoiding fault occurrence in power transformers especially faults which result in transformer fails, became more important for network beneficiaries. Statistical studies show that 70-80 % of power transformers' fails come from inside faults [1-2].

An estimation of transformer faults is shown in figure (1), which shows 10 % occurrence of total winding faults. Among these faults, winding turn is challenging for monitoring and identifying, especially in lower domains of fault current. Usually, this fault begins with a turn connection in winding and gradually result in phase to phase short-circuit fault to earth.

Since various methods are presented and investigated in order to identifying and locating short-circuit faults of wining in power transformers. Some of these methods are based on laboratory work and some other are based on modeling. In each of these methods, an index is used in order to fault identifying.

Differential relays are one of identifying methods for inside faults. In this method the difference between initial and secondary phase currents are monitored continuously as a parameter to identify fault [3].

DGA is one of general fault detection methods which is based on analyzing solution gases. In this method solution gases are analyzed in oil so fault or normal performance of transformer is recognized [3].

Wavelet and neural network transform are among methods that can be used in order to fault detection of transformer [2] and [4-7].

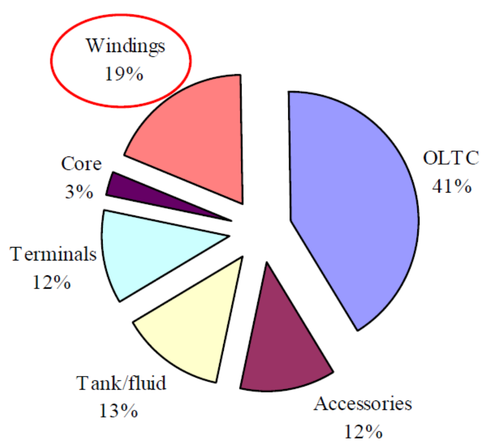

Figure 1- Different fault percentage in transformer [3]

In another method the base of symmetric components' theory or in more exact words sequence currents, is negative. The existence of significant amount of negative sequence currents in transformer's terminal quantities, by itself is a sign of emergence of a disturbance or an index that show non-symmetry that is coupled with this under investigation transformer [4].

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In [8] differential currents are calculated from three phases of turns and measurements' ratios. The set of differential currents are transformed by transforming the park into d-q components. The curves among d and q prove fault of turn connection.

Online analysis of transformer's leakage flux can be used as an efficient method to evaluate accuracy of the machine and recognize the existence of insulating failures during its primary steps. The base of this method is based on recognizing changes in leakage flux because of insulating failure [9].

According to high sensitivity of frequency response to short-circuitfault of wining, among appropriate methods in order to testing winding turn connection, there is wining's frequency response analyze (FRA) [3]. This method is based on this principle that each winding of transformer has its unique transform function and frequency response which is sensitive to changes that are performed in the structure of winding such as resistance, inductance and capacitive changes that finally result in internal faults in transformer. So, identification of winding transformation, winding connection and winding movement and core is possible by this method. By comparing frequency response in fault and intact condition there is the possibility of identification of fault in winding.

Dick and Erven initially demonstrated this method in 1978 [13] for detecting winding deformation under the influence of short circuits. The response in FRA can be categorized broadly as low-frequency, medium-frequency, and high-frequency response. Under the condition of direct short-circuited turns, magnetizing characteristics of the core are changed which change low-frequency response in FRA. Medium-frequency response in FRA gets affected mainly due to the mechanical movement of the winding, e.g., winding deformation, buckling, etc. Localized winding damage causes seemingly random changes in the high-frequency response in FRA [14]. Thus, during inter-turn fault in transformer, low- and high-frequency responses are significant in FRA [15]. In the conventional FRA method, impedance spectrum over the range of frequencies is analyzed using Discrete Fourier Transform (DFT). However, it is mostly observed that the low- and medium-frequency components are insufficient while analyzing using DFT. Thus, the advanced techniques such as synthetic spectral analysis (SSA) based on cut-and-concatenation (CCM) method are used. After spectral analysis of the current set and the reference set, various diagnostic criterions such as sum-squared-error, correlation coefficient, sum squared ratio error, sum squared max-min ratio error, and absolute sum of logarithmic error (ASLE) can be used to determine the fault in the transformer. The combination of SSA (based on CCM) and ASLE has been proved to be most pertinent criterion [16]. Different winding structures give different frequency response in FRA. Winding-to- winding interaction between two different phases and delta connected winding arrangement also affect the frequency response [17]. Although the FRA is generally used to detect the electrical and mechanical faults in windings, its applicability for detection of core fault can also be observed in the literature [18]. The core parameters, such as magnetic permeability, conductivity, and magnetizing impedance, can also be obtained at high frequencies with the help of FRA [19]. However, results obtained from FRA applied to detect the winding faults are not independent of core magnetization. The governing factor in this phenomenon is magnetic viscosity, which is defined as the time dependence of magnetization under a constant magnetic field. The impedance measurement, mainly below 10 kHz, is observed to be significantly dependant on DC magnetization, instances when power supply switches off, and demagnetization [20].

Although, FRA is well-known and popular method in fault diagnostics, this method requires additional sophisticated instruments for the detection. Also, the prediction about the operating condition from the complex admittance-signature is not straightforward and always needs an expert's opinion or evidential reasoning (ER) approach [21].

In this article an efficient method is used to identification and locating turn connection fault. For this reason layer winding of a transformer of a sample distribution is evaluated. To obtain winding frequency response of transformer, first winding is being modeled by described model and parameters are obtained from finite element method, then by the help of MATLAB software winding frequency response is obtained and by comparing fault and intact conditions, turn connection fault is identified and finally fault location is investigated with an appropriate index.

Modeling transformer's winding

The model is being used to describe transformer in frequency finite higher than 10 KHz of described model that is among physical methods of modeling winding. Figure 2 shows the descriptive equivalent turn of transformer. Each unite of this circuit is a turn of winding that includes self and against inductances with other turns. For each turn, capacitor is considered against other turns and with the earth and also ohmic resistance, series with self-inductance. Insulating losses between each two turns are also considered [10]. The smallest component of a winding is its turns. Discs result from being placed on top of each other in radius direction and their connection in vertical direction results in layers of winding.

In order to obtain frequency response, the analysis of equivalent circuit is done in node method and in frequency field. The base of this method is to form admittance matrix from circuit elements. Node equations and admittance matrix are expressed in Equation 1.

$Y.V = I$ (1)

Y, Admittance matrix, is a $2n \times 2n$ matrix that n is the number of winding turns. The vector of nodes' voltage and the current of inductor branches are considered as below.

$V = [V_1, V_2, ..., V_n, I_{L1}, I_{L2}, ..., I_{Ln}]^T{}_{2n\times 1}$ (2)

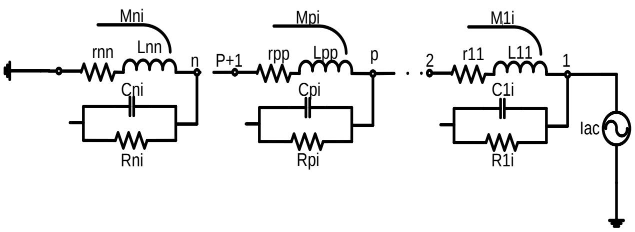


Figure 2- equal circuit of n turns by using described model [10]

Stimulation current vector is expressed as below that I_t is circuit stimulation current.

$I = [I_t, 0, ..., 0, 0]^T$ (3)

Admittance matrix elements of the node are determined as follow that can be different from frequency.

$$Y = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \quad (4)$$

Where:

$Y_{11} = [Cs] + [G(s)], Y_{22} = [Ls] + [R(s)]$ (5)

$$Y_{21} = \begin{bmatrix} -1 & 1 & 0 & . & 0 \\ 0 & -1 & 1 & . & 0 \\ . & . & . & . & . \\ 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & . & 0 & -1 \end{bmatrix} ، Y_{12} = \begin{bmatrix} 1 & 0 & . & 0 & 0 \\ -1 & 1 & . & 0 & 0 \\ . & . & . & . & . \\ . & . & . & . & . \\ 0 & 0 & . & -1 & 1 \end{bmatrix}$$

(6)

By using equation (7) node's voltage is obtained:

$V = [Y]^{-1}.[I]$ (7)

To calculate input impedance, winding has allocated value 1 to the first line of stimulation vector in various frequencies and the values of other lines are equal to zero. In this situation by solving equation (7), the value of node 1 is equal to winding's input impedance. By placing s=jω, the first line of vector V is a mixed number which its size is impedance value and its phase shows inductor or capacitive property in the frequency. Among various windings the order of nodes to each other is different and naturally parameters of the circuit are different in various windings.

Characteristics of transformer and winding

This transformer is a real transformer that is designed and built by Iran University of science and technology, Academic center of education, culture and research. The modeling of transformer and its geometric dimensions are presented in Figures (3) and (4). High-voltage winding belongs to a dry distribution transformer $760^v / 380^v, 10kVA, Dy, U_k = 4\%$.

This winding is composed of 594 turns that are wrapped 6 layers around the core. In each turn one copper conductor with diameter of 1 mm is used. In each turn a green paper is used. According to the existing information we consider the dielectric coefficient of green paper equal to 3, the amount of dielectric coefficient of the insulator equal to 2.8 and the dielectric coefficient for the fiber equal to 4.6.

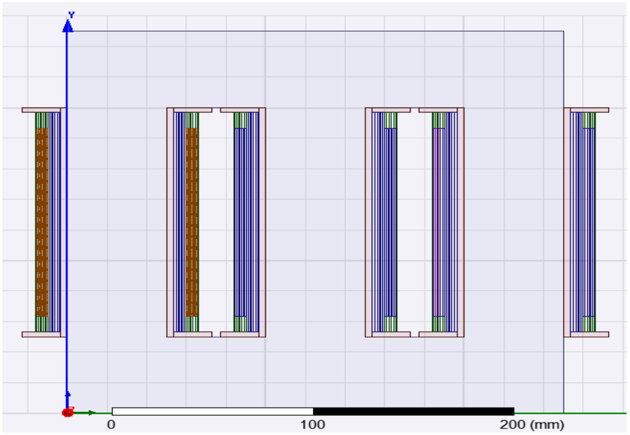


Figure 3- The under investigation transformer

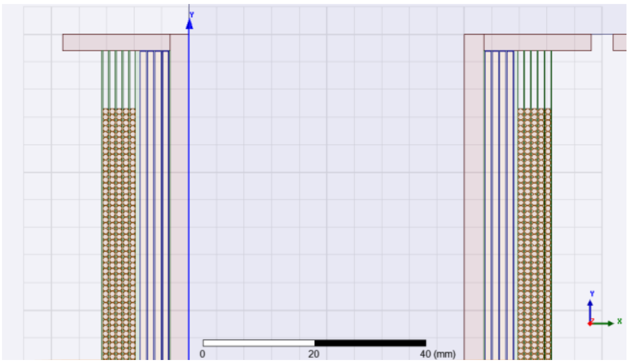


Figure 4 - A view of the under investigation winding

Calculation of descriptive model's parameters

The ability of described model in reconstruction of winding's fluctuation behavior is dependent on the accuracy of calculation of model's parameters. In this article, in order to increase accuracy, finite element method is used to determine winding parameters. For this reason finite element software, MAXWELL 2D, is used.

Inductance calculation: Self-induction related to magnetic flux involves winding which the amount of this flux depends on the density of magnetic flux (B), on the other hand the density of magnetic flux depends on the magnetic permeability of the material used in winding space. The aim of this article is to investigate high frequency behavior ($10^4 - 10^7 Hz$) of transformer winding. In this frequency range, eddy currents are so much that discharge field lines completely out of the core. The center of the core is practically without flux. Filed lines do not enter to the core, but they block their path of air. Iron core behaves like an empty cylinder that there is current in its body. Therefore, we can model the set of iron core and low-voltage winding by an empty cylinder [11]. So the effect of core is not taken into consideration. By dimension determination of turns and identification of materials, finite elements software calculates self and against inductance based on the following equation:

$$L_{ij} = \frac{4W_{ij}}{I^2_{peak}} \quad (8)$$

Where W_{ij} is medium energy which is calculated via field calculations. This software considers the peak current amount for each turn as 1 Ampere, thus the inductance is simplified as $4W_{ij}$. Table 1 shows the amounts of a 6 layer inductance.

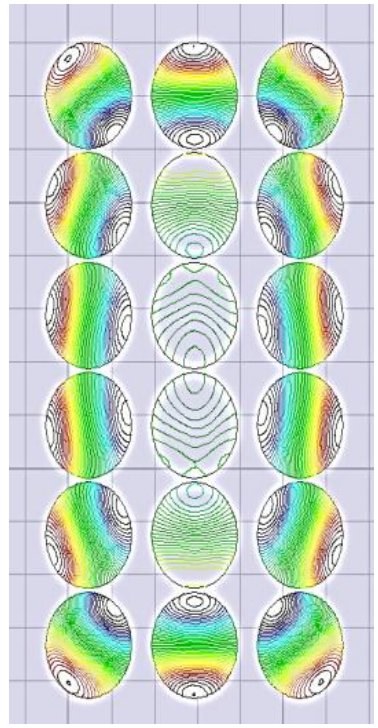
TABLE 1
SELF AND AGAINST INDUCTANCE MATRIX (MH) OF 6 TURNS OF TRANSFORMER WINDING

Turns number	1	2	3	4	5	6
1	L11=2.047	L21=1.854	L31=1.724	L41=1.647	L51=1.591	L61=1.548
2	L12=1.854	L22=2.072	L32=1.859	L42=1.726	L52=1.647	L62=1.591
3	L13=1.724	L23=1.859	L33=2.067	L43=1.864	L53=1.729	L63=1.649
4	L14=1.647	L24=1.726	L34=1.864	L44=2.062	L54=1.865	L64=1.73
5	L15=1.591	L25=1.647	L35=1.729	L45=1.865	L55=2.072	L65=1.862
6	L16=1.548	L26=1.591	L36=1.649	L46=1.73	L56=1.862	L66=2.076
7	L17=1.513	L271=1.548	L37=1.592	L47=1.65	L57=1.728	L67=1.863

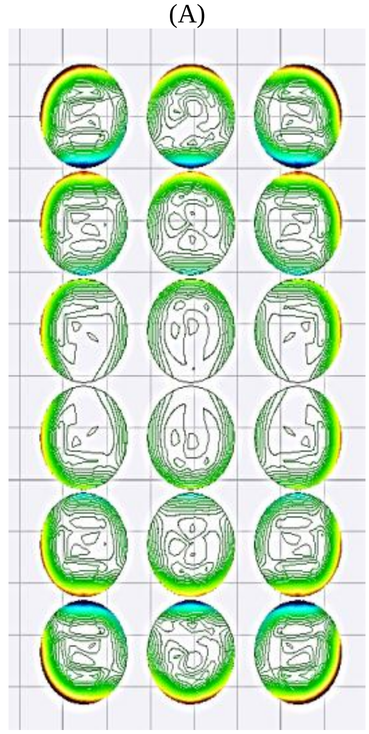
Eddy currents in conductors are because of changing fields with time and we should involve their effect in calculation of inductance matrix, of course, considering this effect in analytic relations is very difficult. The resulted eddy current in conductors cause that the conductor center becomes current free and this results, in the increase of current density in conductor surface, so inductance value decreases. But this effect is more significant on self-inductance value [12].

Figure 5 shows the effect of dermal and proximity influence on current density in several turns in one and thousand KHz frequencies. This element influences the amount of self and against inductances of winding. The amount of inductance of a turn is appropriate to its radius. The decreasing rate of inductance of various turns is approximately the same. In frequency area that inductance amount reaches to its final limit, has relationship with conducting coefficient and conducting transient coefficient.

If there is an investigation in time field, analyzing changing elements with time is very difficult. Therefore, if we can have a good fitting from changing curve of self and against inductance according to frequency, circuit analysis is very useful in frequency field.



(A)



(B)

Figure 5 - Current distribution in some turns of the winding. A: 1KHz B: 1000KHz

The most proper curve which is in harmony with self-inductance changing can be expressed by the following formula.

$$L(f) = ae^{(bf)} + ce^{(df)} \quad (9)$$

So the amounts of inductance are calculated by finite elements in various frequencies and then we can express inductance changes with curve fitting method mathematically. Against inductance changes are few, for this reason we omit against inductance changes than frequency in the performed modeling [10]. By fitting the curve by the help of MATLAB software, fitting curve coefficients are calculated as follow.

$a = 0.0003106, b = -2.935e-8,$

$c = 0.0007683, d = -3.571e-13$

Capacity calculation: Capacities between various elements of windings and core in high frequencies play an important role. The method of distribution of primary voltage on winding is determined by internal capacitive network of the transformer. As the previous part, we determine the capacity amount by modeling in finite elements software. Changes of dielectric coefficient do not make problems in our analysis and usually frequency behavior of dielectric coefficient is not identified. Table 2 shows the amounts of 5 turn capacity.

Resistance calculation

Resistances damp the fluctuations done in inductor and capacitive complex network of winding. It is obvious that without modeling system's resistants we cannot distinguish unstable fluctuations from stable fluctuations. In order to have an accurate resistant modeling, its changes according to frequency are also considered. Resistant increase occur because of the increase of frequency stimulation source due to the movement of current from conducting center to its surface Figure 5, which obtaining its approximate relations analytically is very complicated. By using measurement or finite element method, we can find ohmic resistant amount for each required frequencies.

The method of finding resistant change function according to frequency in order to analyze frequency is very useful. In order to find ohmic resistant fitting according to frequency, the best curve is the exponential curve which is shown below.

$$(10)\ R(f) = ae^{(bf)} + ce^{(df)}$$

In table (3) resistant change of one turn of transformer winding is shown in various frequencies. Fitting coefficients by using MATLAB software are as follow.

$a = 1.426, b = 4.605e-12,$

$c = -1.287, d = -1.84e-8$

TABLE 2

CAPACITY MATRIX (PF)OF FIVE TURNS OF TRANSFORMER WINDING USING MAXWELL2D SOFTWARE

Turns number	1	2	3	4	5
1	C11=403.7	C21=-262.27	C31=-15.98	C41=-9.6689	C51=-6.6206
2	C12=-262.27	C22=611.1	C32=-254.04	C42=-11.516	C52=-6.875
3	C13=-15.98	C23=-254.04	C33=612.39	C43=-252.43	C53=-10.82
4	C14=-9.6689	C24=-11.516	C34=-252.43	C44=614.22	C54=-253.62
5	C15=-6.6206	C25=-6.875	C35=-10.82	C45=-253.62	C55=615.59

TABLE 3

THE AMOUNTS OF THE RESISTANT (OHM) OF ONE TURN OF TRANSFORMER WINDING IN VARIOUS FREQUENCIES

f	1	2	3	4	5	6	7	8	9
R	0.029008	0.029011	0.029014	0.029015	0.029016	0.029017	0.029017	0.029018	0.029018
f	10	20	30	40	50	60	70	80	90
R	0.029018	0.029019	0.029019	0.029019	0.029019	0.02902	0.02902	0.029021	0.029021
f	100	200	300	400	500	600	700	800	900
R	0.029021	0.029025	0.02903	0.029034	0.029039	0.029044	0.02905	0.029056	0.029063
f	1000	2000	3000	4000	5000	6000	7000	8000	9000
R	0.02907	0.029169	0.029321	0.029527	0.029787	0.030101	0.030467	0.030885	0.031353

Calculation of insulating conduction: Because of ideal insulators, their electrical conduction coefficient is against zero. This causes losses in transformer's insulator. By considering a resistant, parallel to capacitor, we can enter insulator losses in the equations. Insulator losses coefficient for capacitor – resistant parallel to capacitor- is as follow.

$$\tan\delta = \frac{1}{R_p C_p \omega} \qquad (11)$$

So by having known insulator losses efficient of one winding unite, we can calculate unknown parallel resistant in the described model. This amount depends on frequency and the properties of insulator loss coefficient impregnated with oil. The amount of insulating loss coefficients for compounds of insulators that exist in one winding unite is estimated through measurement.

$$\tan\delta = 1.082\times10^{-8}\omega + 5.0\times10^{-3} \quad (12)$$

For frequencies of multiple thousand KHz, fixed amount of 0.01 is used as insulating loss coefficient of a winding unite [10].

Model implementation

To solve the described model of transformer, we can get help from circuit solving softwares. To analyze circuit, MATLAB software is used. In order to obtain frequency response a program is written in the context of this software based on node method in frequency field. By using obtained parameters from finite element method and program in MATLAB, input impedance of transformer winding is obtained in various situations. Figure 6 shows frequency response of transformer winding in normal situations.

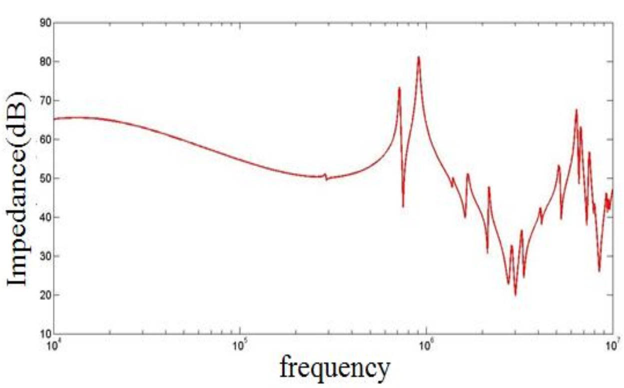


Figure 6- Input impedance of transformer winding (dB) to frequency

Turn-connection modeling

Turn connection occur because of losing insulator between conductors. Qualitatively, we can identify the turn connection equal to increase of insulating conductor between two turns which we can use this method for modeling turn connection.

To form connection matrix, there has been occurred a connection between nodes I and j, with resistant of r_f, we can make elements (j,j), (I,i) of connection matrix equal to $1/r_f$, and make (j,i), (I,j) equal to $-1/r_f$ and the rest of elements equal to zero. Connection matrix is from conduction and it should be coupled with conduction matrix in node method.

Figure 7 shows input impedance of intact winding with stretch line and turn connection with dashed lines. As we can see, turn connection results in domain decrease of input impedance peak and its shift to the right of frequency axis.

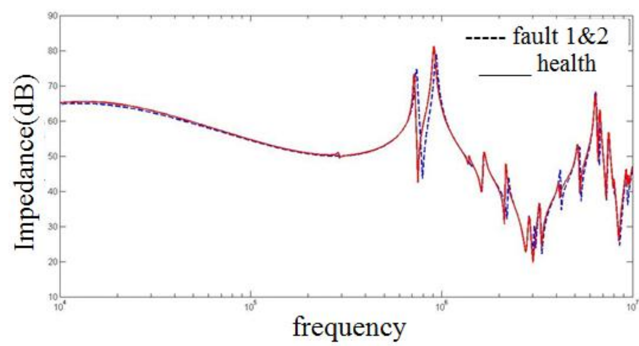


Figure 7- Input impedance of winding (dB) in intact condition and turn connection between the first and second rounds to the frequency

Location of turn connection

Figure 8 shows frequency responses in the existence of turn connection in various places in the top half of the first layer of winding. You can see that the location of turn connection is effective on frequency response.

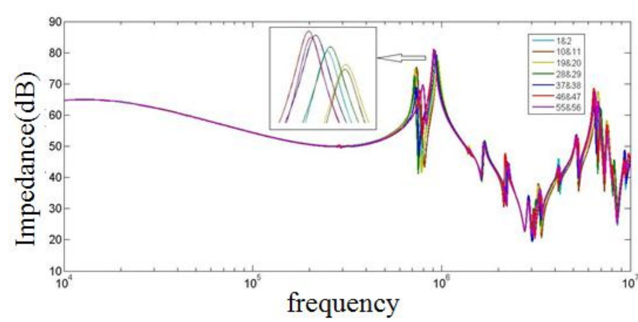


Figure 8- Frequency response of winding with the existence of various faults in the first layer

As it is obvious in Figure 8 the amount of deviations and domain changes depend on fault location. However these changes are very low and there will be obtained no information from visual comparison, so we get help from indexes in order to better comparison. In this step resonance points are studied. Absolute amounts of relative difference in the domain (and frequency) between resonance points have the maximum domain that are chosen as index. This reasoning is obvious in Figure (9).

Following equations express the way of calculation of index.

$$\frac{Df_i}{f_i} = [\frac{f_{o,i} - f_{k,i}}{f_{o,i}}] \qquad (13)$$

$$\frac{DA_i}{A_i} = [\frac{A_{o,i} - A_{k,i}}{A_{o,i}}] \qquad (14)$$

To investigate the under investigation transformer winding in the first layer, 14 parts turn connection winding were done between two turns. The results are in Figures 10-12.

As it is obvious in these figures, obtained indexes are symmetric to winding center. This issue reveals the existence of symmetry between bottom-half of transformer and its top half.

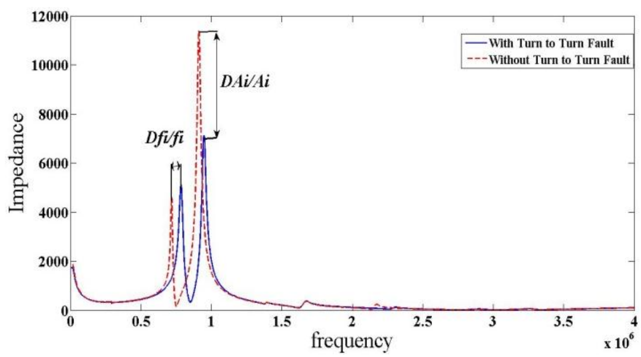


Figure 9- The effect of short circuit on transform function

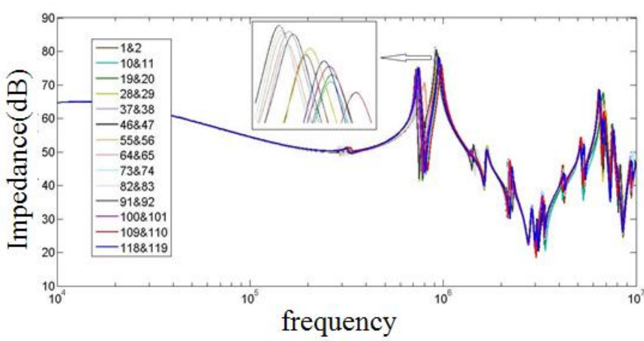


Figure 10- Input impedance of winding (dB) in the existence of fault in various locations of the first layer to frequency

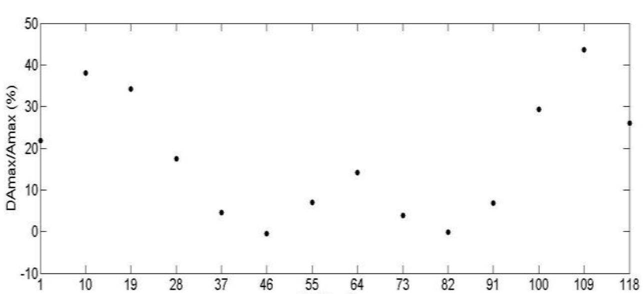


Figure 11- Points dependency to input impedance domain to fault location in the first layer

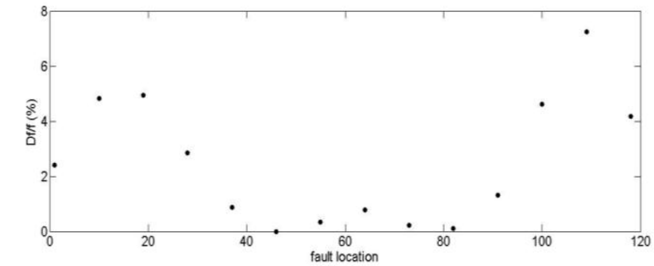


Figure 12- Frequency dependence of maximum points of input impedance to fault location in the first layer

We can also see this symmetry for other layers respectively in Figures 13-20.

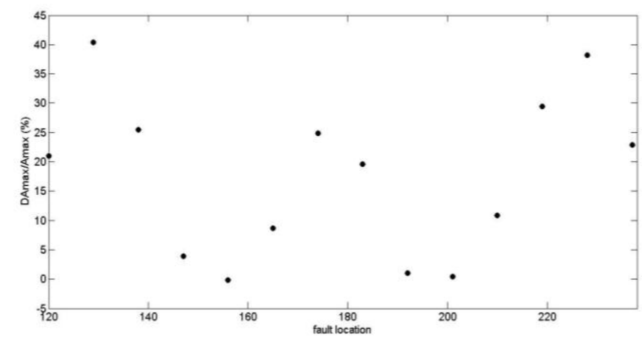


Figure 13- Dependency of maximum points of input impedance to fault location in the second layer

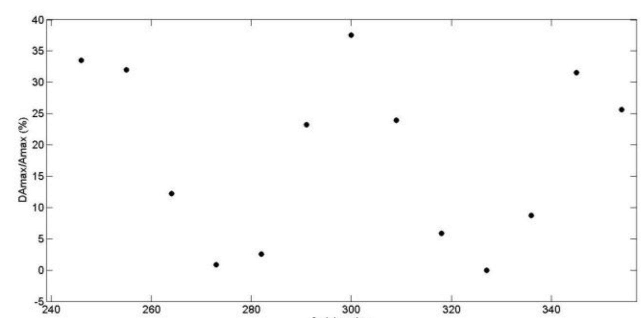


Figure 14- Dependency of maximum points of input impedance to fault location in the third layer

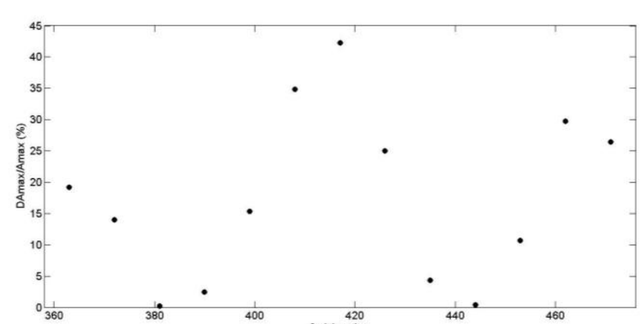


Figure 15- Dependency of maximum points of input impedance to fault location in the fourth layer

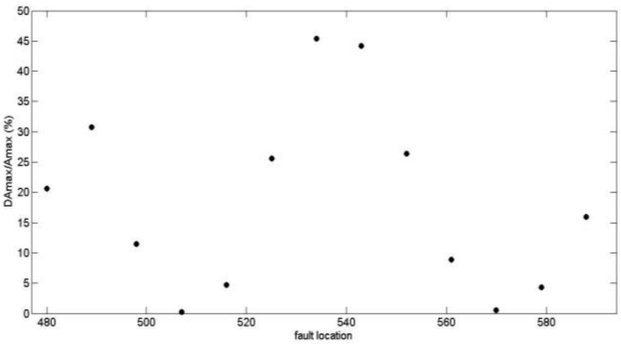


Figure 16- Dependency of maximum points of input impedance to fault location in the fifth layer

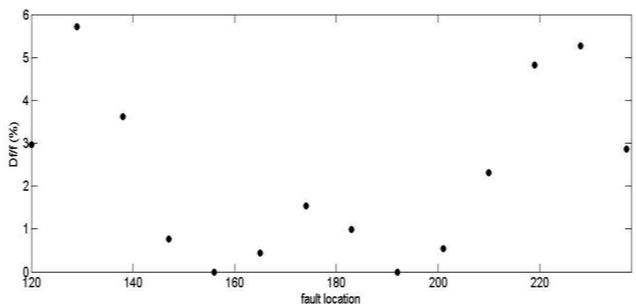


Figure 17- Frequency dependence of maximum points of input impedance to fault location in the second layer.

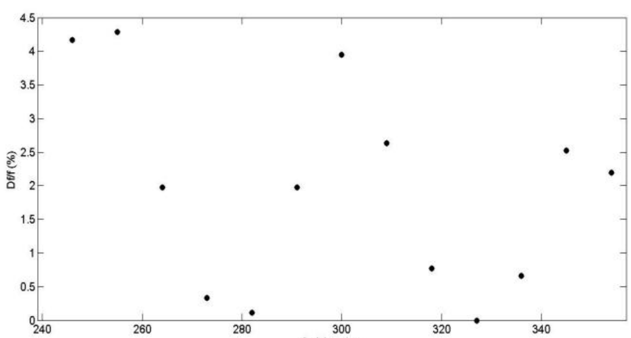


Figure 18- Frequency dependence of maximum points of input impedance to fault location in the third layer

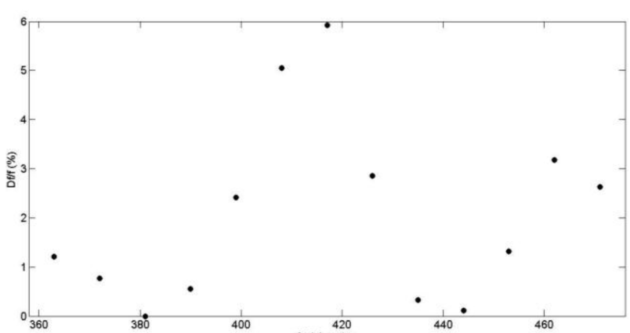


Figure 19- Frequency dependence of maximum points of input impedance to fault location in the fourth layer

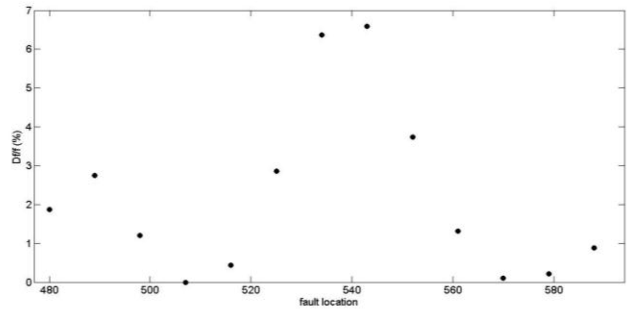


Figure 20- Frequency dependence of maximum points of input impedance to fault location in the fifth layer

Now we focus on fault location change on various layers. Figures (21) and (22) show the indexes for connecting a turn above a winding according to layer number.

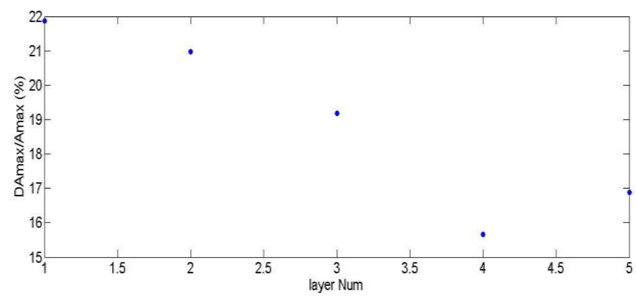


Figure 21- Dependency of maximum points of input impedance according to layer number

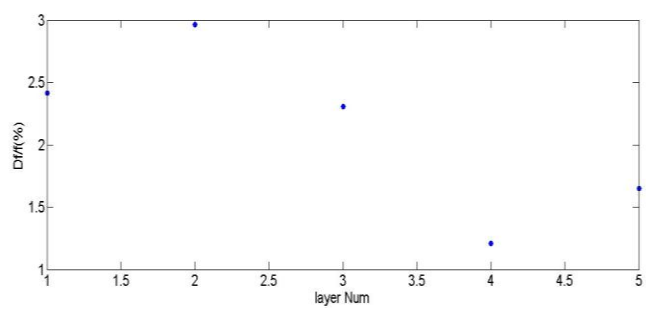


Figure 22- Frequency dependence of maximum points of input impedance according to layer number.

It is seen that fault location on various layers effects on the form of frequency response.

CONCLUSION

In this article frequency response method is used in order to identification and determination of fault location of turn connection. In order to modeling winding, the described model is used. The accuracy of this model is very dependent on its parameter determination. In order to calculate parameters of the described model of winding transformer, finite element method is used which has a good accuracy. By comparing intact and fault mode of frequency response, in resonance points of frequency response, it is obtained that fault mode causes domain change and frequency shift of severe points. The obtained responses in this article have proved the sensitivity of frequency response to fault location in winding. The results of creating connection in various locations of winding show that we have symmetry between top half transformer and bottom half transformer.

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