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Sensitivity Analysis on Ladder Network Equivalent Circuit Parameters of Power Transformer

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CONTENTS

Abstract—In this article, novel methods and ideas are introduced, which altogether lead to an accurate model of power transformer windings. First, by the determination of non-dominant (hidden) resonances from frequency-response tests, a ladder model is proposed. Next, it is improved by assigning different values for similar elements of each section of the model. The parameters are obtained by minimizing the error function via a genetic algorithm. Sensitivity analysis is then applied to the obtained model to achieve further examinations and tests. Measurements have been driven from the windings of a 20/0.4-kV, 1600-kVA transformer. Modeling, methodologies, and sensitivity analysis in this article can be very useful for future research aiming to find internal faults of the transformer with the frequency response analysis.

1. INTRODUCTION

High-voltage transformers are important parts of power systems; hence, their performance, behavior, and condition in power systems have been of interest to many researchers. One key step toward analyzing the behavior of transformers is to find a suitable model for them. Also, one of the things that contributes greatly to the analysis of the behavior of power transformers is that the model has the ability to analyze the behavior of power transformers in high frequencies, which is due to the fact that most of the faults that damage or even disable the transformers, for example, lightening and switching, happen in high frequencies.

In this regard, researchers have found feasible models for transformers [1–4]. Some of these models are physical [5, 6], black box [7, 8], and hybrid [9] models. A physical model that has drawn much attention is the ladder network model. Among the most important features of this model, in addition to the ability of analyzing in high frequencies, is that it can be changed depending on the type and the number of windings; and for various transformers, models with different levels according to the complexity and accuracy of the model can be presented. It should be noted that this also makes it easier to explain the modeling physically. One of the solutions to

Keywords: frequency response analysis, power transformer windings, genetic algorithm, ladder network, sensitivity analyze
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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uemp.

achieve a more accurate transformer model and for estimating the parameters of the equivalent circuit is frequency response analysis (FRA) [5, 7, 10]. This method could be applied to report even the smallest changes or relocation of the winding. Thus, it is widely used to detect internal defects of transformer windings [10–12].

In this study, sensitivity analysis of the transformer (0.4:20 kV, 1600 kVA) equivalent ladder circuit compared to its self-inductance and mutual inductance is analyzed using frequency response. This study could be addressed in problems regarding detection and locating mechanical defects within transformer windings. To do this, it is necessary to find a precise ladder network of a transformer [10]. By applying this model for obtaining parameters of the ladder network of the transformer, and by using sensitivity analysis, the most sensitive level compared to the changes of self- and mutual inductance will be identified. By comparing the original frequency response to the altered response and by using sensitivity analysis, this method can be used efficiently to analyze the cause of the possible fault. Since each change can be mapped in the frequency response obtained by sensitivity analysis to relative change in inductance, the location of the fault can be found easily and efficiently.

2. LADDER NETWORK MODEL

As previously mentioned, the ladder network is used to model transformer windings. In this article, this model is used for experiments and simulations. A ladder network with n sections and mutual coupling that represents transient behaviors of windings is pictured in Figure 1. Each section of the ladder equivalent circuit represents one group of disks. Also, in spiral type transformers, it can represent the number of turns of windings [6, 13]. Although this model is simpler than models based on the traveling-wave theory [14] and multidisciplinary transmission theory [15], it has feasible physical aspects [16]. It should be noted that to obtain satisfactory results from the ladder network, the number of parts should be equal to or greater than the number of peaks in the frequency response diagram [17, 18]. Therefore, if the measured frequency response of a transformer has n peaks, then it will be necessary to model an equivalent ladder circuit of at least n sections.

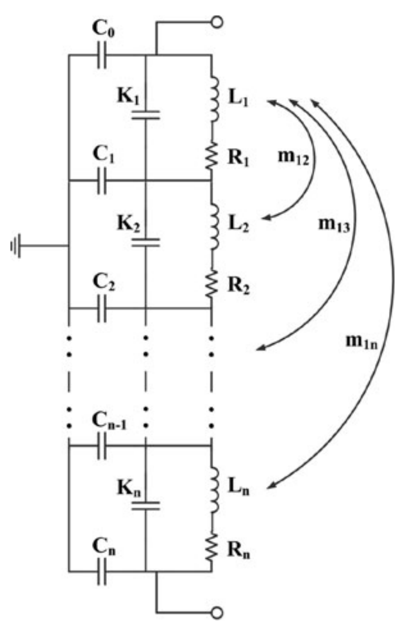

FIGURE 1. Scalar network model circuit of n levels.

In this modeling, defining resistance, capacitance, and inductance values is important because the results of the FRA depend on these values. These symbols are used for circuit parameters:

C_i: capacitance of the earth, modeled as capacitance between section i and the core or the tank;
K_i: series capacitors, modeled as capacitance between two consecutive sections;
L_i: self-inductance of part i;
R_i: series resistors of part i; and
M_{ij}: mutual inductance, modeled as mutual inductance between parts i and j.

All the parameters are in nanofarads, millihenries, and kΩ The five parameters above are the main components of the ladder network model and are also physically feasible. Finding the exact value of these parameters has the most important role in achieving an accurate and reliable model.

3. DETAILS

3.1. Practical Details and Measurement Results

The goal at this stage is to determine the ladder network of an actual transformer, and to that end, a 0.4:20-kV, 1600-kVA transformer has been analyzed. The input impedance seen between sections of different disks of transformer high voltage (HV) windings and the ground was measured using an impedance analyzer model (Wayne Kerr B6500, Wayne Kerr Electronics Inc., Woburn, MA, USA), and the corresponding diagram is shown in Figure 2. As can be seen in Figure 2, this diagram has seven peaks, which represent resonant frequencies of the transformer; it can therefore it can be realized from this diagram that to achieve a more accurate result, a ladder equivalent circuit consisting of seven levels must be considered, as discussed previously.

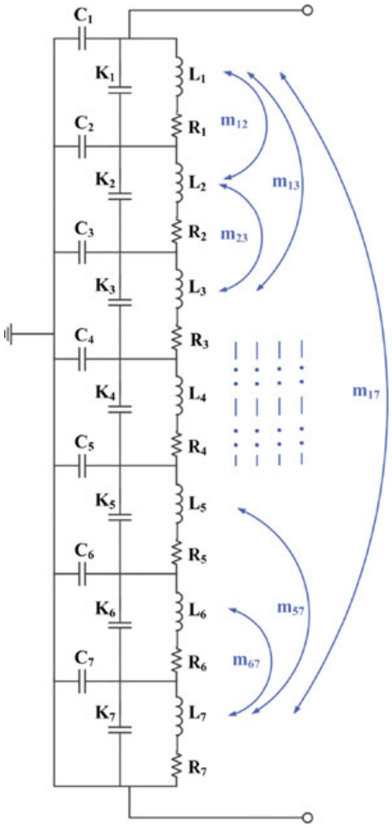

FIGURE 2. Seven-part equivalent scalar network, representing HV windings simulated using MATLAB.

3.2. Ladder Equivalent Circuit Consisting of Seven Sections and Its Specifications

As shown in Figure 2, a ladder network of seven sections for the HV winding of the transformer is simulated using MATLAB (The MathWorks, Natick, Massachusetts, USA). Figure 2 also shows that the equivalent model is made of electrical elements, the amount of which effect the FRA results; it is thus necessary to determine the exact amount of these elements.

The amount of each element is considered to be different in different sections. It should be noted that acceptable values of self- and mutual inductance in the ladder network model should follow the following inequality to be physically true [2]:

$$\begin{aligned} L_{ab} &< L_{aa} \quad \text{and} \quad L_{ab} < L_{bb}, \\ L_{ab} &> L_{cd} \quad \text{if} \quad |c-d| > |a-b|, \\ (L_{ab} - L_{ac}) &> (L_{ac} - L_{ad}) \quad \text{if} \quad |a-b| \\ &< |a-c| < |a-d|. \end{aligned}$$

4. PROBLEM DESCRIPTION

In this article, c_i, k_i, l_i, r_i, and m_{ij} have different values. This matter makes the modeling more realistic and valid for inhomogeneous windings. It should be mentioned that the assumption of the equality of values of similar parameters limits the solution to homogeneous windings that may lead to less accurate results.

Furthermore, some physically justifiable constraints should be taken into account to verify the ladder network parameters. The distance between two sections affects their mutual inductance [19], and therefore, the following inequality should be considered:

$$m_{ij} > m_{nk} \quad \text{if} \quad |n-k| > |i-j|. \tag{1}$$

It is clear that the self-inductance of a section is more than its mutual inductances with every other sections, and thus,

$$m_{ij} < l_i \quad \text{and} \quad m_{ij} < l_j. \tag{2}$$

The following inequality was proposed and verified recently in [2]:

$$\begin{aligned} (m_{ij} - m_{ik}) > (m_{ik} - m_{in}) \quad \text{if} \quad |i-j| \\ < |i-k| < |i-n|. \end{aligned} \tag{3}$$

It has been proven that if the FRA measurement results of a transformer has N resonances, then an equivalent circuit with at least N sections will suffice to represent the model, and the results will be satisfactory [2, 4].

However, in this article, hidden resonances will be also taken into account to have results that are more accurate. The number of hidden (non-dominant) resonances is around N – 1. The FRA test of the transformer used herein has four dominant and three non-dominant/hidden resonances. Therefore, an equivalent seven-section ($2N$ – 1 sections) ladder network can be used to model and simulate the winding.

5. ERROR FUNCTION

The goal in this section is to minimize the error (difference) between the measured and simulated FRA results. The error function between two curves—the reference FRA test, denoted by r_i, and the simulated FRA result, denoted by s_i—is defined as follows [16, 20]:

$$EF = \sum_{i=1}^{P} \frac{1}{P} \sqrt{\left[\frac{s_i - ((s_i + r_i)/2)}{(s_i + r_i)/2}\right]^2 + \left[\frac{r_i - ((r_i + s_i)/2)}{(r_i + s_i)/2}\right]^2}, \tag{4}$$

where P is the number of measured points.

A new approach used herein is to emphasize resonance areas in EF using some specific coefficients. In other words,

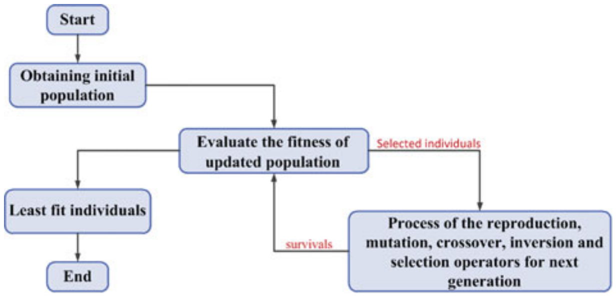

FIGURE 3. Simple diagram representing the GA process.

Parameter	Value
Selection function	Stochastic uniform
Population type	Double vector
Scaling function	Rank
Population size	700
Generations	300
Initial penalty	10
Penalty factor	100

TABLE 1. Parameters of GA

the points in the FRA tests that are near resonance points will have higher weighting factors. Therefore, the improved *EF* version can be rewritten as Eq. (5). This equation can noticeably increase the accuracy of tracing resonance points in the FRA tests that are more important than other points. Furthermore, it significantly accelerates the convergence speed of the process:

$$EF = \frac{\sum_{i=1}^{P} \omega_i \cdot \sqrt{\left[\frac{s_i-((s_i+r_i)/2)}{(s_i+r_i)/2}\right]^2 + \left[\frac{r_i-((r_i+s_i)/2)}{(r_i+s_i)/2}\right]^2}}{\sum_{i=1}^{P} \omega_i}, \quad (5)$$

where ω_i is the weighting factor of point i. As discussed earlier, ω_r assigned to the points in resonance areas is higher than ω_j allocated to the points out of these regions.

6. OPTIMIZATION PROCESS

The genetic algorithm (GA) is an evolutionary heuristic approach in the artificialintelligence field that mimics the process of natural evolution. The algorithm starts with a population of solutions (usually randomly), then improves it through repetitive process of reproduction, mutation, crossover, inversion, and selection operators. A simple GA procedure can be written as follows [21].

a. Choose the initial population of individuals;

b. Evaluate the fitness of each individual in that population;

c. Select the best-fit individuals for reproduction;

d. Breed new individuals through crossover and mutation operations to give birth to offspring;

e. Evaluate the individual fitness of new individuals;

f. Replace the least-fit population with new individuals'

Figure 3 is a simple diagram that represents the GA procedure.

The problem has 50 unknown parameters (21 of which are mutual inductances) and 42 constraints. Theses unknown parameters and the significantly limited search area make the solution finding process very difficult. Table 1 shows the parameters used in the GA solver of MATLAB.

7. TEST RESULTS

For the above-mentioned case, the parameters are determined using a GA and are based on the comparison between measured and simulated FRA results. All cases are studied using the

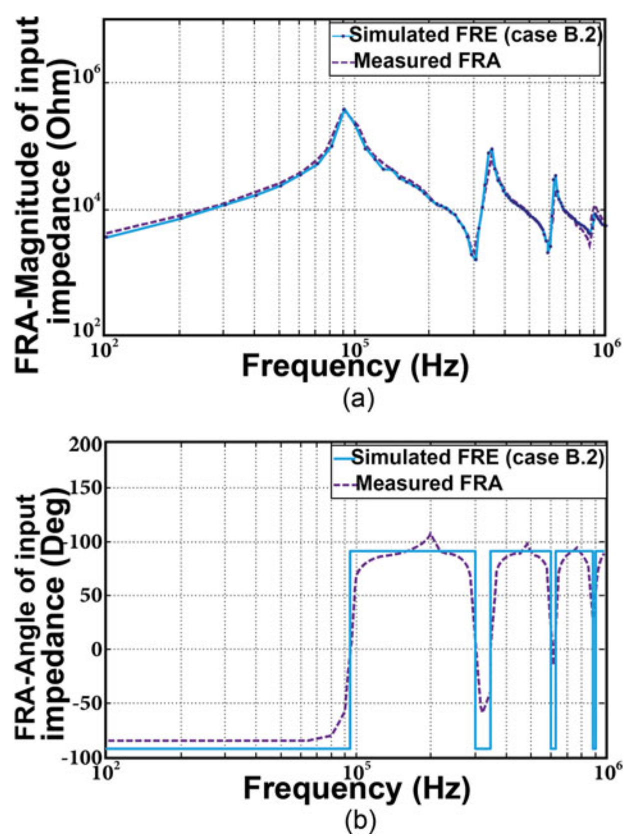

FIGURE 4. Measured and simulated FRA results for seven-part equivalent scalar network: (a) magnitude and (b) angle.

characteristics summarized in Table 1 for the GA toolbox of MATLAB.

Figure 4 illustrates the measured FRA result and the result of the proposed method for simulated FRA. Obtained parameters of the seven-section ladder network are tabulated in Table 2. Figure 4 demonstrates that the accuracy of the proposed method is high. The method could find a solution that covers all resonances correctly; furthermore, *EF* obtained is 0.12, which is satisfactorily low.

8. SENSITIVITY ANALYSIS OF FRA

In most studies, the earth capacitance is simply changed to model winding movements, while small changes in self- and mutual inductance can have considerable influence on frequency response. In this research, most of the attention is on how this change can influence frequency responses and their effect on frequency response and rate of destruction for finding the rate of sensitivity of frequency responses. In this regard, it can be reviewed from two perspectives.

1. How does the increase or decrease of inductance of one section influence frequency response?
2. How do the rates of inductance influence of each section compared to other sections?

r_1 (Ω)	0.0825	m_{34}	3.9327
r_2	0.0931	m_{35}	1.4601
r_3	0.0584	m_{36}	0.9710
r_4	0.0961	m_{37}	0.2071
r_5	0.0931	m_{45}	0.6906
r_6	0.0544	m_{46}	0.0644
r_7	0.0553	m_{47}	0.0282
l_1 (*m*H)	9.8077	m_{56}	0.1039
l_2	1.1946	m_{57}	0.0282
l_3	7.0576	m_{67}	0.7502
l_4	4.8540	c_0 (nF)	4.0375
l_5	1.0851	c_1	1.9457
L_6	1.6951	c_2	1.9665
l_7	1.7606	c_3	4.5158
m_{12}	0.5670	c_4	4.5415
m_{13}	0.2716	c_5	4.3646
m_{14}	0.1241	c_6	2.9999
m_{15}	0.1120	c_7	0.8013
m_{16}	0.0806	k_1	1.6147
m_{17}	0.0782	k_2	1.1555
m_{23}	1.0953	k_3	1.1717
m_{24}	0.1319	k_4	0.0927
m_{25}	0.0450	k_5	1.3399
m_{26}	0.0377	k_6	9.7902
m_{27}	0.0085	k_7	1.4181

TABLE 2. Parameters of the simulated ladder network

8.1. Small Changes of Self-inductances

For this purpose, two stages are simulated. In the first stage, about 20% of self-inductance of each section is decreased and the diagram of impedance is drawn. In the second stage, as in the first, self-inductances are increased about 20%. It can be noted that for a better view, figures 5–11 are enlarged around the first peak frequency response of transformer.

8.2. Small Changes of Mutual Inductance

As for the previous part, changes in self-inductances lead to change in frequency response. Also, changes on mutual inductance can also influence frequency response. To review the influence of mutual inductance, as in the first stage, decreases of 20%, one by one, should take place, and then the diagram of the section is drawn. For better analyzing and showing the influence of variations of mutual inductances, the diagram of influences of inductance between first section and other sections (m_{12}, m_{13}, m_{14}, ...), and similarly between the second section and sections below (m_{25}, m_{24}, m_{23}, ...), were drawn separately.

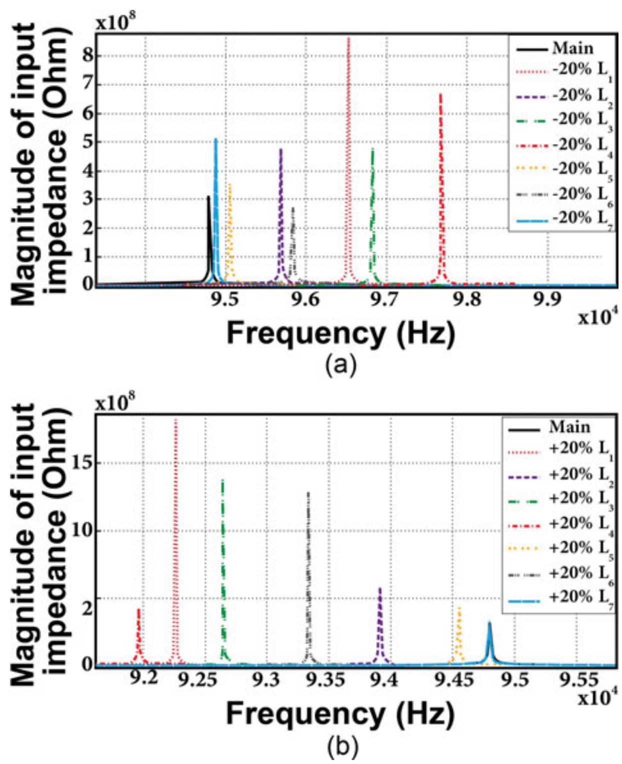

FIGURE 5. Small changes of self-inductance.

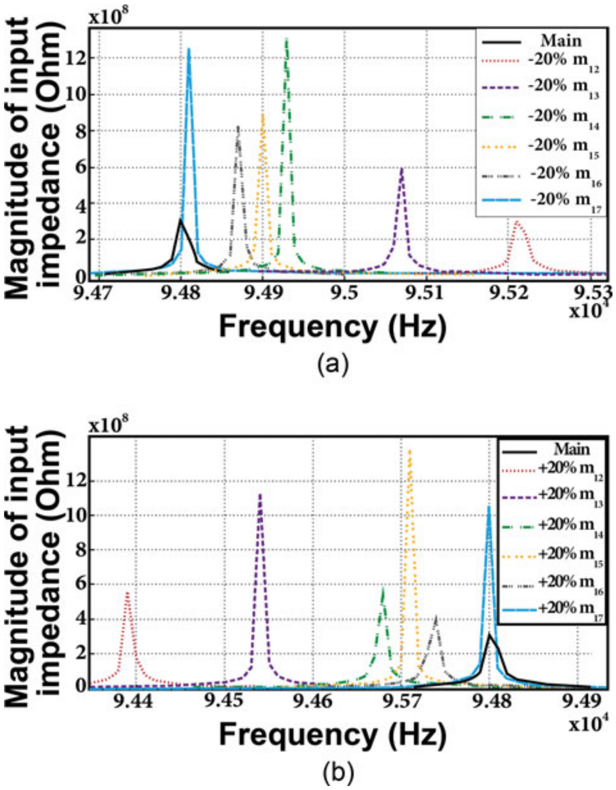

FIGURE 6. Small changes of mutual inductance between section 1 and other sections.

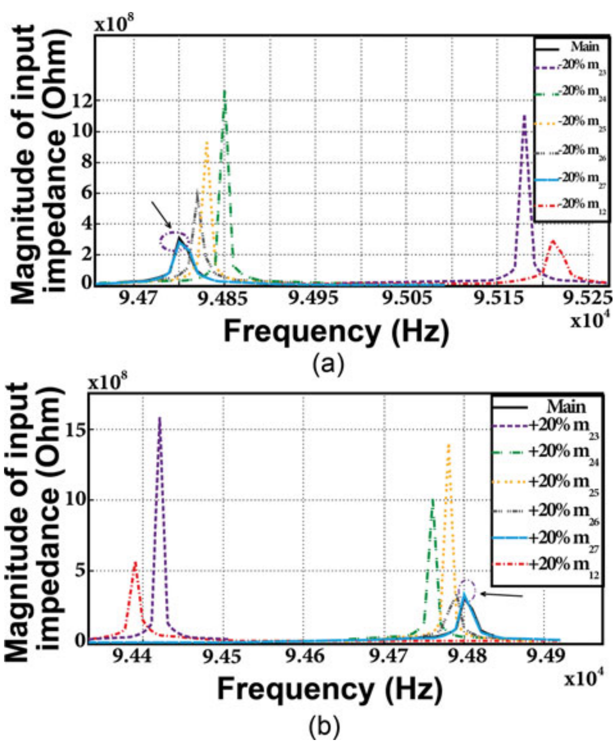

FIGURE 7. Small changes of mutual inductance between section 2 and other sections.

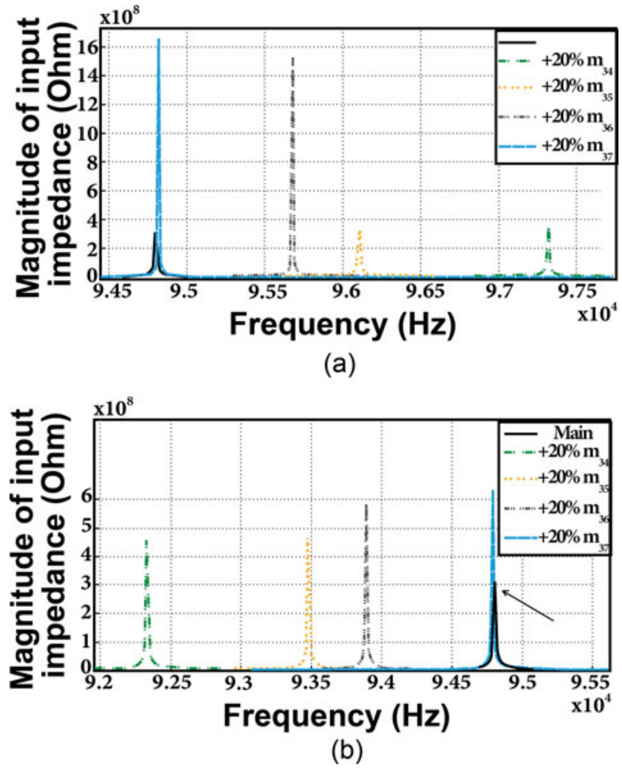

FIGURE 8. Small changes of mutual inductance between section 3 and other sections.

9. ANALYZING THE RESULTS

Here the obtained results are analyzed. It should be mentioned that to maintain consistency, only the first resonant frequency is analyzed in all cases. It can be seen in Figure 5 that to change self-inductance for –20%, all of the first resonant frequencies changed remarkably. This issue is expected, since the resonant frequency is quality related to amounts of C and L. But the rate of these changes is completely different in FRA. Referring to Figure 5, it is quite obvious that the highest transition in resonant frequency would be due to L_4, and the least destruction would be because of L_7. According to Figure 5, the response for any incremental variation in L_4 has the most sensivity and in L_7 has the least sensivity. The point is that increasing L_7 would approximately have no effect on resonant frequency. It is known that each section of the ladder model or electrical equivalent circuit plays a representative roll in the real transformer; *e.g.*, the middle section of equivalent circuit shows the exact behavior of the winding group, located in the middle of transformer. It is known intuitively that the middle winding in a transformer is subjected to a relatively high amount of magnetic flux; so the amount of inductance is rather high in the middle winding rather than windings located nearby. Considering the fact that the amount of L_4 is more than L_7

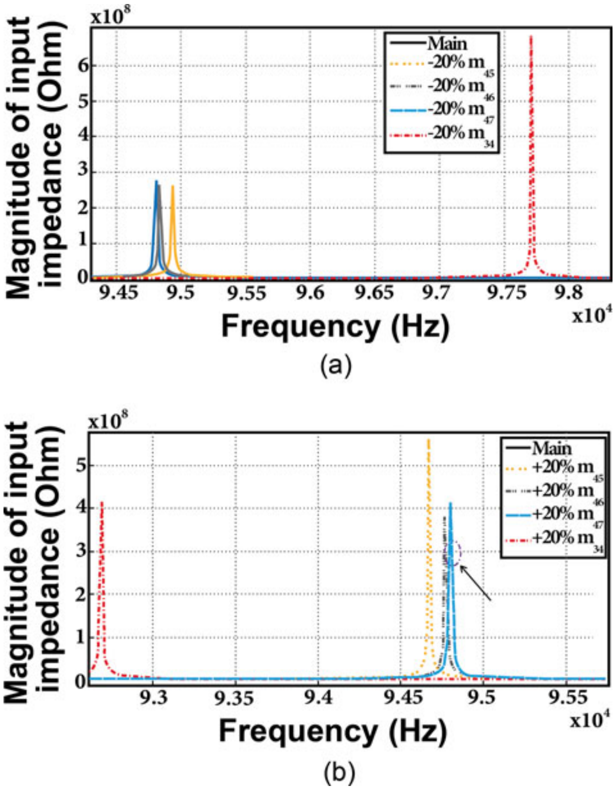

FIGURE 9. Small changes of mutual inductance between section 4 and other sections.

and the fact that it is located in the center of the transformer's winding, increasing, decreasing, or removing L_4, which may cause transformer damaging, could change the impedance of a ladder network more effectively; it can also be predicted that changing in this manner would widely result in changing resonance places. The results of the simulation show that reducing self-inductances makes the resonant frequency move to the right, and the incensement in self-inductances lead to a switch in the first resonant frequency to the left side.

The results of the simulation are depicted in Figures 6 to 11, which are about changes of mutual inductances showing that decreasing self-inductances shifts the first resonant frequency to the right and increasing makes the movement to the left. This phenomenon also occurs for mutual inductances between section 1 and other sections, so the frequency response shows the most sensivity to m_{12} and the least sensivity to m_{17}. Besides special discipline, this issue is not unexpected, because the distribution flux because of coil 1, which also includes other coils, has a declining rate due to the increase in the distances of coils, thus giving

$$m_{17} < m_{16} < m_{15} < m_{14} < m_{13} < m_{12}.$$

According to these changes (its decrease or increase), other mutual inductances related to coil 1 would be more, so their

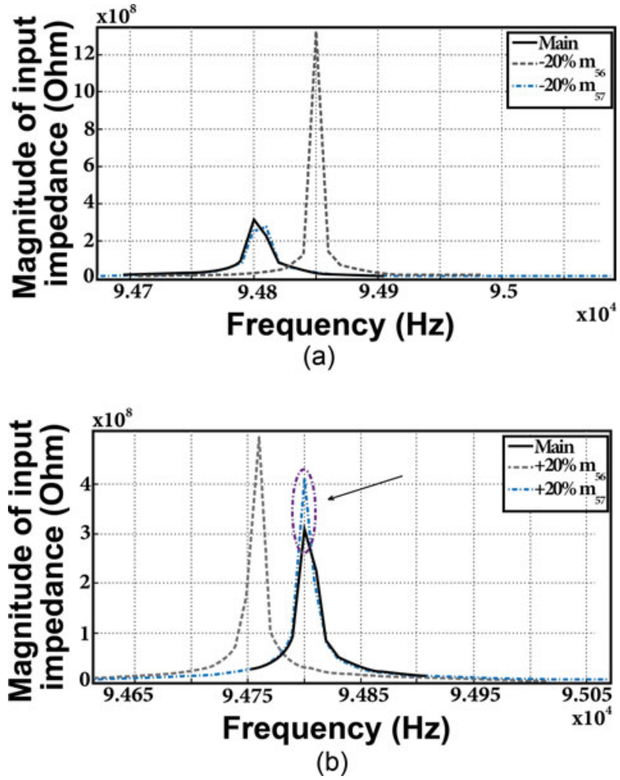

FIGURE 10. Small changes of mutual inductance between section 5 and other sections.

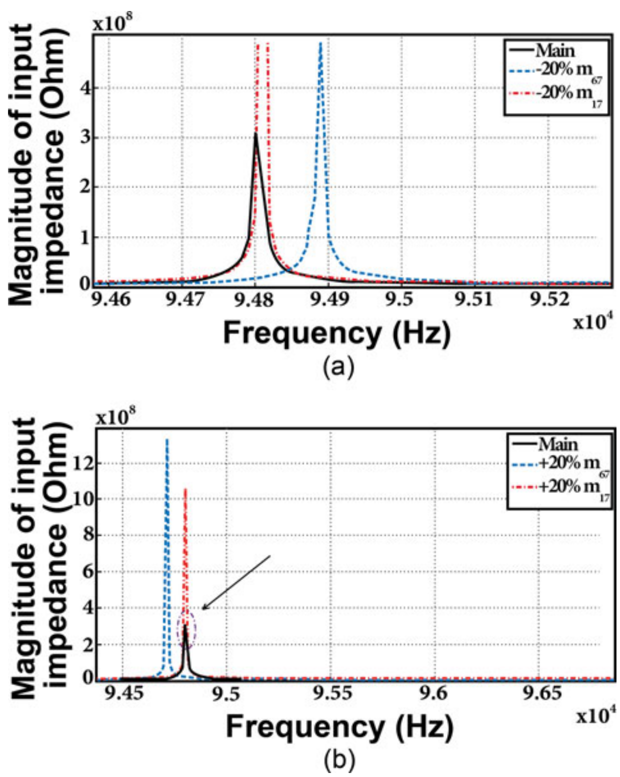

FIGURE 11. Small changes of mutual inductance between section 6 and other sections.

FIGURE 12. Schematic of experiment of AD fault.

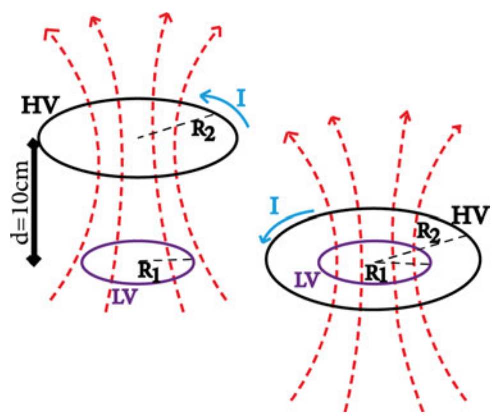

FIGURE 13. Simplified model of high- and low-voltage winding in transformer experiencing AD.

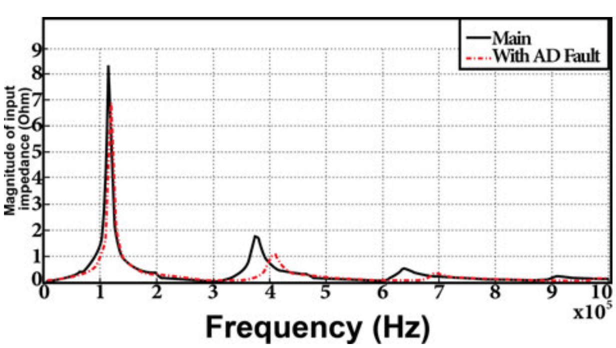

FIGURE 14. Effect of AD fault on frequency response of the transformer.

effect on frequency response would be greater. The results for other sensitivity analysis related to other coils shown in various figures also prove the previous arguments.

In Figure 7, showing mutual inductance between coil 2 and other coils, besides the diagrams for $m_{23}, m_{24}, \ldots$ changes, the diagrams for m_{12} changes are also given. It is obvious from this figure that m_{12} changes have more effect on frequency response. In this and other figures, some points are marked with arrow sign. This is to emphasize the fact that the diagrams for change of elements will change slightly or not at all.

10. EXPERIMENTAL RESULTS

Experimental works were conducted on the same transformers mentioned in simulation section. It can be seen in Figure 12 that the high-voltage winding of the transformer is subjected to an axial displacement (AD) fault in which the high-voltage winding is shifted upward by 10 cm. This would affect the mutual inductance and, thus, the total impedance of the winding. Figure 13 shows a simplified model of the transformer's winding in this experiment. As it is obvious from Figure 13, the amount of magnetic flux flow to the low-voltage winding decreases as the high-voltage winding is displaced, so intuitively, it is expected that mutual inductance would decrease when increasing the distance between windings. The output impedance of the transformer is measured according to the frequency by using impedance analyzer (Wayne Kerr B6500). Frequency response data from these two experiments, one with the shifting and the other without shifting, are depicted in Figure 14 using MATLAB for comparison. It can be seen in Figure 14 that the peaks are shifted to the right with regard to peaks from the original structure. Since this shift is to the right, it justifies the previously mentioned fact regarding decrease in mutual inductance.

11. CONCLUSION

The ladder transformer model is used in this research to analyze the sensitivity. This is because of finding the effect of changing the self-inductance and mutual inductance on frequency response. Simulation results suggest that among self-inductances, the class 4 inductance has the most effect and class 7 inductance the least effect on frequency response. For mutual inductance, the declining process of mutual inductance effects between the target and other coils is obviously seen. It can also be said that the simulations showed that the movement of the first resonant frequencies to the right is because of the decrease of self- and mutual inductances, and their movement to left is because of the increase of self- and mutual inductances. These points can be useful tips in fault detection of a transformer.

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