Ladder Network Parameters Determination Considering Nondominant Resonances of the Transformer Winding

Masoud M. Shabestary, Ahmad Javid Ghanizadeh, G. B. Gharehpetian, and Mojtaba Agha-Mirsalim

***Abstract*—In order to accurately model the transient behavior of transformer windings, we need models with a large number of nodes and parameters. This paper proposes a model that has fewer nodes and can accurately predict the behavior of a transformer in a wide range of frequencies. In the proposed method, based on the terminal measurements, N dominant resonances are determined, and it is experimentally shown that the winding has $N-1$ hidden resonances. Using this idea, we suggest the use of a $2N-1$ section ladder network, which has a minimum number of nodes and can accurately model the behavior of the transformer winding. The parameters of this model are determined by minimizing the error function by using the genetic algorithm. The close agreement between the simulation and measurement results on the windings of a 20/0.4-kV and 1600-kVA transformer verifies the accuracy of the proposed method.**

***Index Terms*—Frequency-response analysis (FRA), genetic algorithm (GA), ladder network, power transformer windings.**

I. Introduction

IN POWER transformers, mechanical flaws, such as the displacement or deformation of the windings, may occur and cause disastrous failures [1]. Therefore, the monitoring of in-service transformers can significantly reduce failure rates and reduce outage costs.

Among different surveying methods, frequency-response analysis (FRA) is the method most frequently used in recent papers [1]–[5]. To find the mechanical defects of transformer windings, the FRA results for normal and fault conditions are compared. Mechanical flaws affect these results. The location and number of differences in the test results between the normal and fault conditions can help power-utility engineers detect faulty cases. To study and find the reasons for variations in the FRA results, developing an accurate equivalent model for transformer windings is essential.

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Different attempts have been made to present reasonable and exact models of transformer windings, including physical [6]–[8]; black-box [9], [10]; and hybrid models [11]. Reference [6] used the R-L-C-M elements to model a noninterleaved double-disc winding. Mukherjee *et al.* [2] presented a fully coupled ladder network with five sections and analyzed it based on the information on the driving-point impedance. In this model, the winding length was mapped to a few sections of a ladder network. The researchers found that the number of sections of the ladder network modeling a typical transformer winding depends on the number of winding sections. Also, the number of sections affects its FRA test results. Ladder network modeling has been used with six sections in [4] using the driving-point impedance function resulting from FRA measurements.

Reference [11] found that the analytical methods for the parameter identification of a transformer winding model were not accurate enough to fully model the behavior of transformer winding with a wide range of frequencies. Therefore, some evolutionary approaches have been recently applied to discover the most suitable parameters for different models. These approaches have involved the use of optimization algorithms, such as the artificial bee-colony algorithm [2]; bacterial swarming algorithm [3]; and genetic algorithm (GA) [6].

Rashtchi *et al.* identified different parameters of the transformer winding by presenting an R–L–C–M model [6]. These researchers used the GA as a tool to reduce the difference between the measured and simulated FRA results. However, to reach this goal, they made the following simplifications:

- neglecting the small mutual inductances;
- assuming similar values of the R–L–C–M parameters for different sections of the ladder network;
- focusing on the high-voltage (HV) winding without modeling the low voltage (LV) to achieve practical results.

Recently, [2] and [4] proposed physically realizable parameter identification methods with special constraints and inequalities, which will be discussed in the following sections. Despite this realistic approach, they still made some simplifications implementing a few sections for all types of windings, using the same values for the elements in all sections, neglecting the resistances, and considering only the dominant resonance frequencies in the error function. In addition, the researchers did not consider enough unknown parameters.

This paper proposes a method that does not depend on simplifications. The authors apply the proposed identifying method to the FRA results of a 20/0.4-kV transformer with a rating of 1600

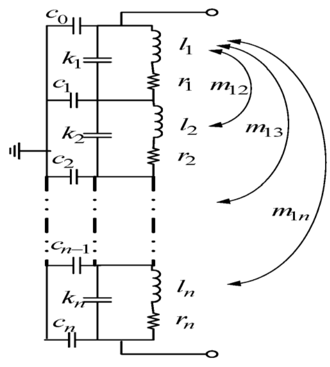


Fig. 1. Ladder-network model for the HV winding.

kVA. Next, the GA finds the best values for different parameters of the model of the windings and minimizes the error function (EF) between the measured and simulated FRA results. Finally, the authors compare their results with those from the methods used in the recent studies.

II. Ladder Network Model

An n-section mutually coupled ladder network shown in Fig. 1 is used as the model in this paper. This network can also be used for fault detection and diagnosis. Each section of the ladder network usually represents a group of discs in disc-type windings as well as one or a few turns in helical-type windings [12]–[14]. This model is simple compared to those based on traveling-wave theory [15], [16] and multiconductor transmission-line theory [17]–[19], but its parameters can be physically justified, and it can accurately demonstrate the transient behaviors of the transformer windings.

Since the results of the FRA tests are related to the values of the resistances, capacitances, and inductances of the ladder network, these values must be determined exactly [20], [21].

The following circuit elements define the parameters of the ladder network:

c_i	ground capacitance, which models the capacitance between the ith section and the tank or the magnetic core;
k_i	series capacitance, which models the capacitance between sections i and $i-1$;
l_i	self-inductance of the ith section;
r_i	series resistance of ith section;
m_{ij}	mutual inductance between the ith and jth sections.

All of the above circuit elements are taken on a per-section basis in units of nF, mH, and kΩ, respectively. These five parameters are the main parameters of the ladder network that can be physically justified.

The FRA results depend on the geometrical characteristics of the winding and, thus, the variations in these parameters due to mechanical flaws can lead to variable FRA test results. Therefore, obtaining the accurate values of the parameters plays a key role in developing a reliable model.

III. Problem Description

In this paper, c_i, k_i, l_i, r_i, and m_{ij} have different values in each section. This approach makes the modeling more realistic and valid for inhomogeneous windings. However, the assumption of the equality of the values of similar parameters in each section limits the solution to homogeneous windings and may lead to less accurate results for inhomogeneous ones.

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 [22] and, therefore, the following inequality should be considered:

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

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

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

Mukherjee and Satish have recently proposed and verified the following inequality [2]:

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

According to the first and second inequalities, "$m_{13} < m_{12} < \min(l_1, l_2)$" should be satisfied in the parameter determination problem. In addition, the third inequality states that, for example, "$(m_{12} - m_{13}) > (m_{13} - m_{14})$" is a realistic constraint that governs the relationship between the first three adjacent sections of a winding in homogeneous structures.

It was found that if the FRA measurement results of a transformer had N resonances, then an equivalent circuit with N sections sufficed to represent the model, and the results were satisfactory [2], [4]. However, this paper will show that some resonances are hidden in a specific FRA test. Therefore, to have more accurate results, the hidden (nondominant) resonances should also be considered. Fig. 2 shows the input impedance of a transformer winding measured at different nodes ($Z_{i,0}$ for $i = 1, \ldots, 19$). The measurements are based on the methods presented in [11], with an open-circuited LV winding. These nodes are the connecting points of the double-discs in a winding. The bold curve in Fig. 2 and the list in Table I show that the input impedance measured between the double-disc 19 and the ground ($Z_{19,0}$) has four dominant resonances: R1, R3, R5, and R7. Thus, N is equal to 4, and a 4-section ladder network can be used. However, in this figure, one can also recognize three nondominant resonances R2, R4, and R6. Therefore, an equivalent 7-section ("$2N - 1$" sections) ladder network can be used to model and simulate the winding.

IV. Error Function

The goal of this section is to minimize the error (the difference) between the measured and simulated FRA results. Ji *et al.* defined the error function between the two curves, namely, the "reference FRA" denoted by r_i, and the "simulated FRA result" denoted by s_i as in the following [1]:

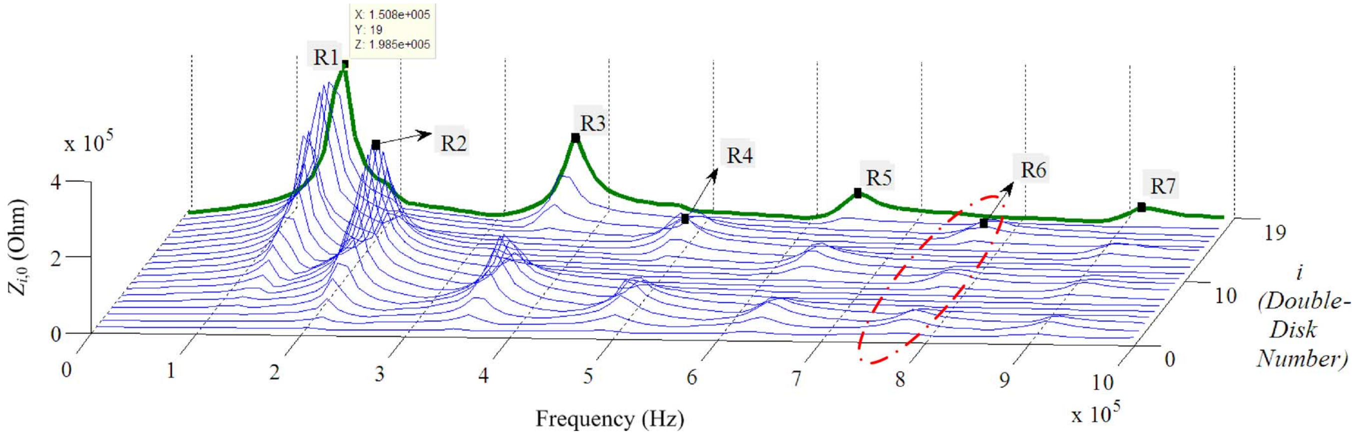


Fig. 2. FRA test results: The input impedance between the jth double-disc and the ground (for $j = 1, \ldots, 19$).

TABLE I
MEASURED INPUT IMPEDANCES OF THE RESONANCE POINTS BETWEEN THE *get* DOUBLE-DISC AND THE GROUND FOR $j = 1, \ldots, 19$

Dominant and non-dominant resonances	R1	R2	R3	R4	R5	R6	R7
Resonance frequency (kHz)	150	202	343	484	626	768	899
$Z_{1,0}$ (kΩ)	0.63	1.70	2.95	3.80	3.89	4.75	4.55
$Z_{2,0}$ (kΩ)	3.19	8.55	13.21	14.84	14.36	14.8	11.7
$Z_{3,0}$ (kΩ)	7.20	27.05	30.20	33.00	23.88	17.2	10.2
$Z_{4,0}$ (kΩ)	12.22	53.96	60.43	48.71	24.72	11.4	5.52
$Z_{5,0}$ (kΩ)	16.27	101	90.98	46.74	13.85		
$Z_{6,0}$ (kΩ)	22.45	113.4	86.92	31.36			
$Z_{7,0}$ (kΩ)	27.94	152.6	84.87	15.48			6.01
$Z_{8,0}$ (kΩ)	46.24	207.8	69.59			6.68	12.9
$Z_{9,0}$ (kΩ)	92.00	258.7	38.56			16.8	9.74
$Z_{10,0}$ (kΩ)	169.9	235.5	17.01		12.26	18.8	
$Z_{11,0}$ (kΩ)	232.2	362.1			27.29	9.96	
$Z_{12,0}$ (kΩ)	239.9	283.6		9.30	28.73		3.93
$Z_{13,0}$ (kΩ)	223.8	229.9		24.47	17.96		9.55
$Z_{14,0}$ (kΩ)	258.4	145.5		42.92	8.31		13.4
$Z_{15,0}$ (kΩ)	214.8	66.63		50.52		9.37	8.03
$Z_{16,0}$ (kΩ)	255.4	31.83	7.96	42.07		18.9	
$Z_{17,0}$ (kΩ)	481.9	17.12	23.67	22.60		19.5	
$Z_{18,0}$ (kΩ)	363.2		53.43	10.53	9.09		8.25
$Z_{19,0}$ (kΩ)	398.5		73.29		20.79		11.17

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

where P is the number of measured points.

This paper utilizes a new approach to emphasize the resonance areas in the EF by using some specific coefficients. In other words, in the FRA tests, the points that are near resonance points will have higher weighting factors. Therefore, the improved version of the EF will be as in (5). In the FRA tests, this equation can noticeably increase the accuracy of the tracing of the resonance points that are more important than the other points. Also, (5) significantly accelerates the convergence speed of the process. ω_i is the weighting factor of the point i. As discussed before, the ω_r assigned to the point in the resonance areas is higher than the ω_j allocated to the point out of these regions

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

In [1] and [23], the EFs obtained by using (4) are, respectively, 0.35 and 0.502 in the best cases. In this paper, the EF will reach 0.12. This result will be discussed in Section VIII.

V. Optimization Process

Because of the GA's fast convergence, high efficiency, and accurate results [23], this paper uses the GA to minimize the error function. The GA, an evolutionary heuristic approach in the artificial-intelligence field, mimics the process of natural evolution. The algorithm starts with a population of solutions (usually a random one) and then improves it through the repetitive process of reproduction, mutation, crossover, inversion, and selection operators. A simple GA procedure is described as [24]:

a) choose the first 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 offsprings;
e) evaluate the individual fitness of each of the new individuals;
f) replace the least-fit population with the new individuals.

VI. Studied Cases

In this paper, Cases A and B are studied and simulated by using a 4-section and 7-section ladder network, respectively. Each case has two subclasses. The subclasses A.1 and B.1 have equal values for the same elements in each section of the ladder network. The second subclasses A.2 and B.2 have different values for the same elements in each section of the ladder network.

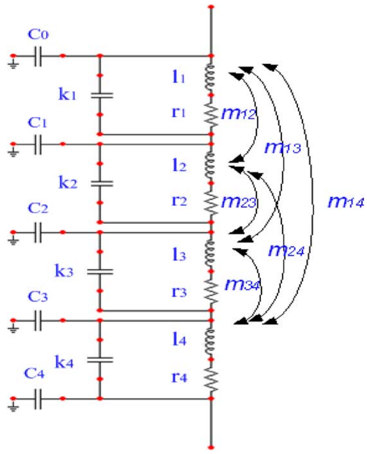


Fig. 3. Four-section ladder network simulated by the ATP–EMTP.

Fig. 4. Test setup.

A. Case A

The goal is to find a simple ladder network with a minimum number of sections to cover all resonance points with an acceptable EF value. In [2] and [4], the reference FRA has N resonances that suggest at least an N-section ladder network. Therefore, the FRA test shown in Fig. 2 requires at least a 4-section network. Fig. 3 displays this network simulated by the ATP-EMTP software for the transformer winding shown in Fig. 4. The impedance analyzer (Wayne Kerr Precision Impedance Analyzer 6500B Series) shown in Fig. 4 takes the reference FRA test of this winding. The analyzer has a precision of more than 99.9% for frequencies up to 30 MHz [25]. The GA toolbox of MATLAB minimizes the error between the reference measured and the simulated FRA results.

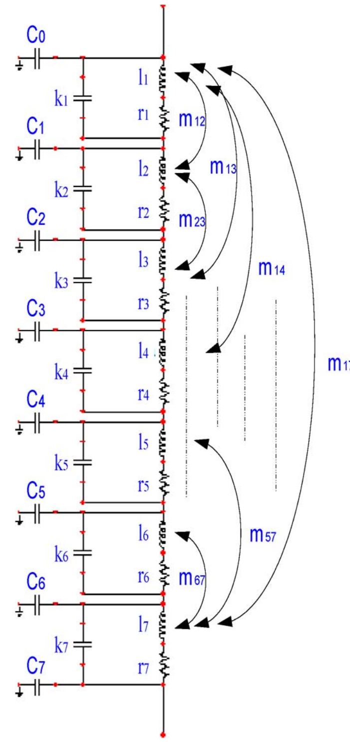


Fig. 5. Seven-section ladder network simulated by the ATP–EMTP.

TABLE II
DATA OF THE FOUR DIFFERENT CASES

Case	Number of sections	Value of elements	Number of unknown parameters	Number of constraints
A.1	4	Identical	7	3
A.2	4	Different	23	12
B.1	7	Identical	10	6
B.2	7	Different	50	42

B. Case B

As discussed in Section III, to obtain more accurate results, this paper also considers the number of the nondominant resonances. Thus, in this case, the same tests used in Case A are taken on a 7-section ladder network instead of a 4-section network.

VII. PARAMETERS AND CONSTRAINTS

Compared to the number of unknown parameters and applied constraints used in pervious papers, the number used in this paper is noticeably higher to improve the accuracy. For instance, there are 50 unknown parameters and 42 constraints in case *B.2* shown in Fig. 5. The proposed method accurately obtained their values. Table II lists the number of unknown parameters and necessary constraints for all cases.

TABLE III
PARAMETERS OF THE GA

Parameter	Value
Selection Function	Stochastic Uniform
Population type	Double Vector
Scaling Function	Rank
Population size	700
Generations	300
Initial Penalty	10
Penalty Factor	100

A. Case A.1

This case has seven unknown parameters r, c, k, l, $m_{12} = m_{23} = m_{34}$, $m_{13} = m_{24}$, and m_{14} with three constraints as follows:

$$l > m_{12} > m_{13} > m_{14}. \quad (6)$$

These inequalities show the distance relationship of the inductances between the various sections of the ladder network of a winding [2], [4].

B. Case A.2

In this case, there are 23 unknown parameters r_i, c_i, k_i, and l_i (for $i = 1, \ldots, 4$), c_0, m_{12}, m_{13}, m_{14}, m_{23}, m_{24}, and m_{34}.

Moreover, each mutual inductance has two constraints, resulting in a total of 12 constraints as shown

$$l_1 > m_{12}, \quad l_2 > m_{12} \quad (7)$$
$$m_{12} > m_{13}, \quad l_3 > m_{13} \quad (8)$$
$$m_{13} > m_{14}, \quad l_4 > m_{14} \quad (9)$$
$$l_2 > m_{23}, \quad l_3 > m_{23} \quad (10)$$
$$m_{23} > m_{24}, \quad l_4 > m_{24} \quad (11)$$
$$l_3 > m_{34}, \quad l_4 > m_{34}. \quad (12)$$

Applying all of these constraints is time-consuming and may prevent the GA from searching all possible solutions. This paper implements a novel idea to change the approach by using the factors $\alpha_1, \alpha_2, \ldots, \alpha_6, (0 < \alpha_i < 1)$ instead of m_{12}, m_{13}, m_{14}, m_{23}, m_{24}, and m_{34} as unknown parameters. For instance, instead of applying inequalities of (7), it is definitely easier to use the following equation:

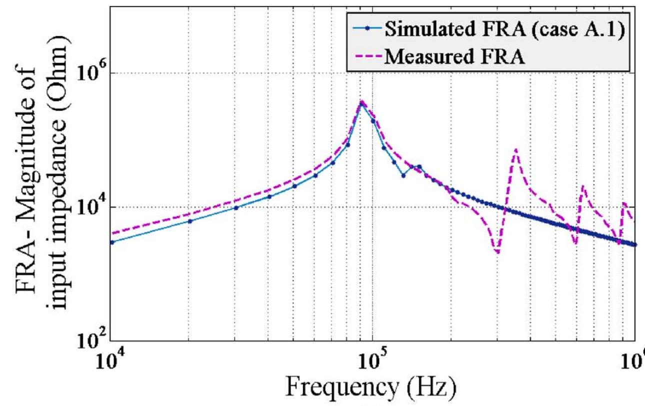
$$m_{12} = \alpha_1 . \min(l_1, l_2). \quad (13)$$

This approach can easily solve the problem without applying the constraints (7)–(12).

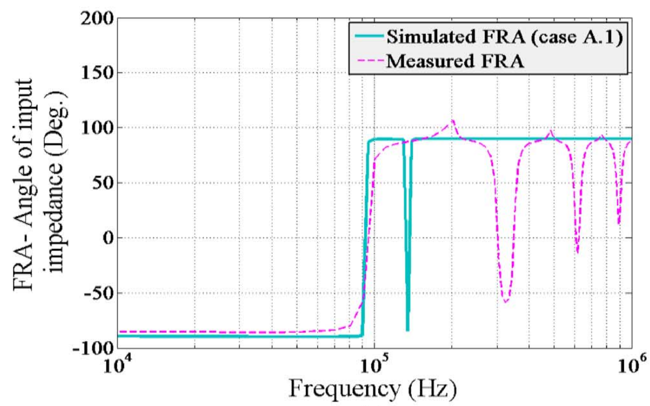
C. Case B.1

This case consists of 10 unknown parameters $r, c, k, l, m_{12} = m_{23} = m_{34} = m_{45} = m_{56} = m_{67}, m_{13} = m_{24} = m_{35} = m_{46} = m_{57}, m_{14} = m_{25} = m_{36} = m_{47}, m_{15} = m_{26} = m_{37}, m_{16} = m_{27}$, and m_{17}. Also, six constraints exist as follows:

$$l > m_{12} > m_{13} > m_{14} > m_{15} > m_{16} > m_{17}. \quad (14)$$



(a)



(b)

Fig. 6. Measured and simulated FRA results for case A.1: (a) magnitude and (b) angle.

D. Case B.2

The most difficult case in this paper is Case B.2, which has 50 unknown parameters (twenty-one of them are mutual inductances) and 42 constraints. These unknown parameters and the significantly limited search area make finding a solution very difficult, even though the idea introduced for Case A.2 can help to solve the problem.

VIII. TEST RESULTS

For the four aforementioned cases, the parameters are determined by using GA and are based on the comparison between the measured and simulated FRA results. The GA toolbox of the MATLAB simulates all of the cases by using the same characteristics summarized in Table III. Figs. 6 and 7, respectively, show the results for Cases A.1 and A.2, with the parameters listed in Table IV. The figures illustrate that the accuracy of Case A.2 is greater than that of A.1. However, as Table V shows, the convergence time in Case A.2 is approximately twice that of Case A.1.

Figs. 8 and 9 illustrate the results for Cases B.1 and B.2, ,respectively, with the parameters tabulated in Table VI. As shown in Fig. 8, Case B.1 covers only the first two resonances and is not able to find a possible solution that covers the third and fourth resonances. Fig. 9 shows that the accuracy of Case B.2 is greater than that of Case B.1. Case B.2 can find a solution that covers all resonances correctly. Moreover, as Table V reveals, the EF of Case B.2 is less than that of Case B.1 by almost 64%.

TABLE IV
PARAMETERS OF CASES A.1 AND A.2

	A.1	*A.2*		*A.1*	*A.2*
$r_1(\Omega)$	8.2932	0.2726	m_{24}		1.9449
r_2		2.7795	m_{34}		2.3715
r_3		7.1893	c_0 (nF)	0.0295	0.0219
r_4		5.5291	c_1	0.0591	0.2050
l_1 (mH)	8.4787	9.9901	c_2		1.8422
l_2		8.0911	c_3		1.9654
l_3		9.9656	c_4		0.1366
l_4		9.2017	k_1	0.1528	0.0799
m_{12}	1.0794	7.3252	k_2		0.0535
m_{13}	1.0668	0.6674	k_3		6.4228
m_{14}	0.5096	0.6535	k_4		0.0393
m_{23}		2.0135			

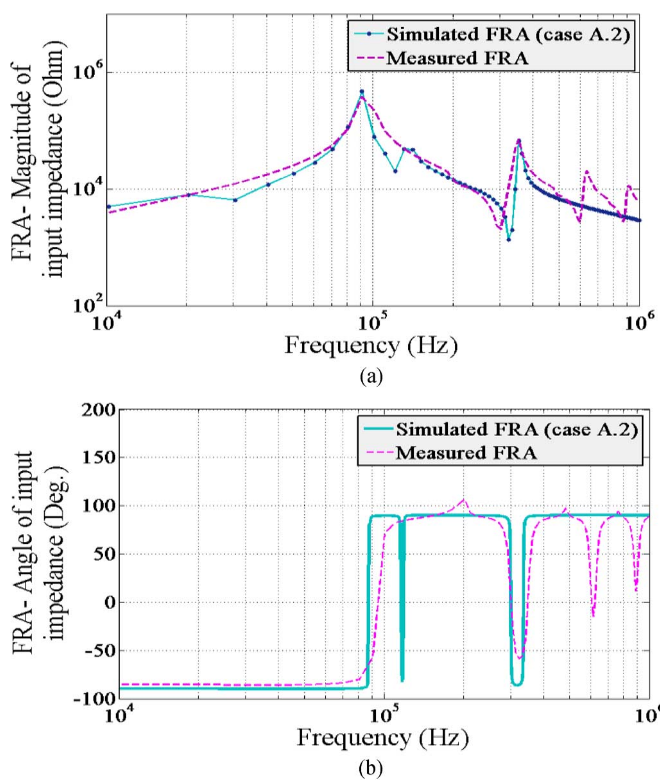


Fig. 7. Measured and simulated FRA results for case A.2: (a) magnitude and (b) angle.

TABLE V
RESULTS OF THE FOUR CASES

Case	Population size of GA	Generation size of GA	Convergence time (Hour)	*EF*	Number of Covered resonances
A.1	700	300	4	0.65	1
A.2	700	300	7	0.55	2
B.1	700	300	5	0.33	2
B.2	700	300	9	0.12	4

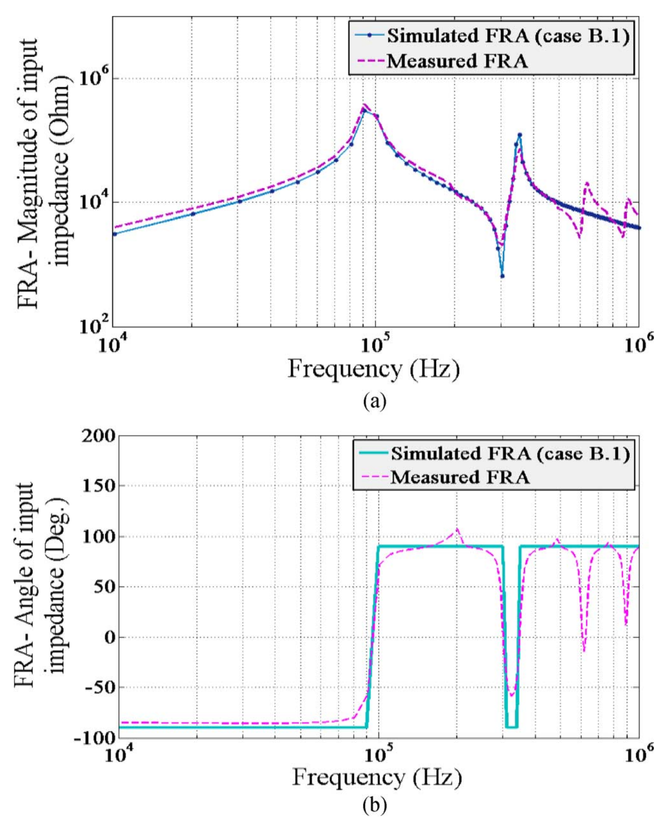


Fig. 8. Measured and simulated FRA results for case B.1: (a) magnitude and (b) angle.

IX. DISCUSSION

As mentioned in pervious sections, in order to reach the minimum number of sections in the modeling with the aim of covering all resonances and obtaining accurate results, the number of resonances is important. Hence, if the input impedance measurement from the terminal displays four resonances, and the internal measurements of the impedances (from all individual double-discs) show three more resonances (which are the hidden resonances), then two cases will be simulated and analyzed; the four-section and the seven-section (considering the dominant and the nondiminant resonances) ladder networks.

As indicated in the previous sections, Cases A.1 and B.1 are not supportive enough to cover all resonances. Therefore, this paper proposes using the model of case B.2 to overcome the problem of the FRA curve covering. Although this model cannot

TABLE VI
PARAMETERS OF CASES B.1 AND B.2

	B.1	*B.2*		*B.1*	*B.2*
r_1 (Ω)	0.0315	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 (mH)	1.8256	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)	2.9824	4.0375
l_5		1.0851	c_1	5.9649	1.9457
L_6		1.6951	c_2		1.9665
l_7		1.7606	c_3		4.5158
m_{12}	1.5031	0.5670	c_4		4.5415
m_{13}	1.3019	0.2716	c_5		4.3646
m_{14}	0.3465	0.1241	c_6		2.9999
m_{15}	0.1536	0.1120	c_7		0.8013
m_{16}	0.1399	0.0806	k_1	1.0202	1.6147
m_{17}	0.1095	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

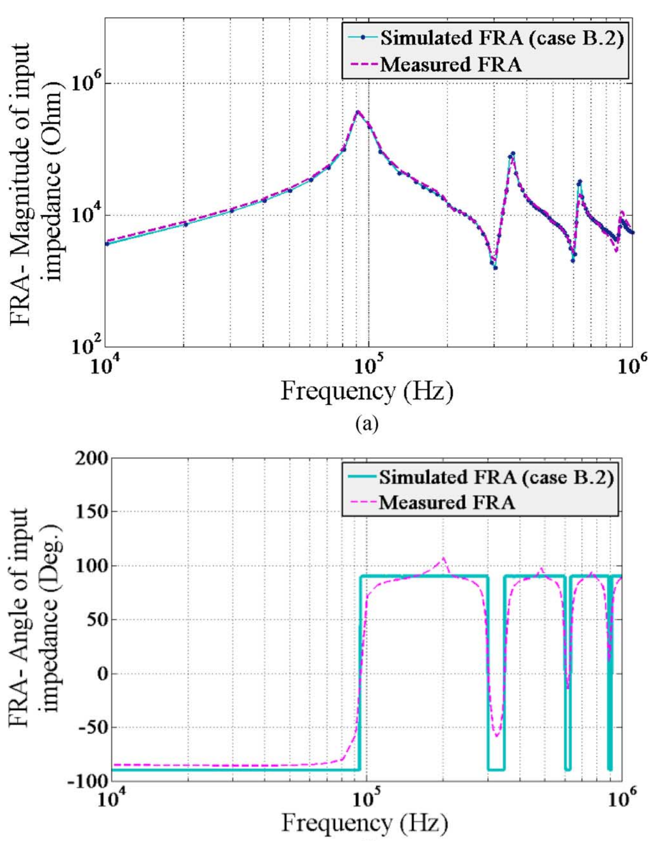


Fig. 9. Measured and simulated FRA results for case B.2: (a) magnitude and (b) angle.

completely fit the reference curve and the simulated curve together, it gives a remarkable result with a satisfactory EF. In fact, the 38 discs (each containing 20 or 21 turns) in the winding are modeled by just seven sections. Hence, with this degree of simplicity, the obtained result is highly significant. This paper aims at finding a simple and accurate method to cover all resonance points in the FRA by modeling a 38-disc H-V winding with a seven-section inhomogeneous ladder network equivalent circuit.

If a structural change, such as a short circuit between the turns, occurs inside the transformer, then the structure of the ladder model itself should change for Cases A.1 and B.1. The main advantage of the B.2 case over B.1 is that if a structural change occurs inside the transformer, then by assigning different values for the same elements of the various sections, these structural changes and the differences between sections will be taken into account, and the results will still be satisfactory.

The measurements used in this paper cannot be exactly applied to extract the internal resonances of an individual double disc because it cannot be divided into more than two individual sections to obtain the data sets needed to find the internal resonances. Moreover, even if the disk is divided into its turns, the modeling should be changed. The ladder network modeling is well suited to the cylindrical winding structures. Other modeling methods, such as the hybrid model, should be used for other kinds of transformers. However, this method can be used with some modifications to model the individual double discs.

Each section of the ladder network corresponds to a certain length and a certain number of discs. In fact, the first section of the winding corresponds to the first section of the model. For example, the 150th turn is in the 8th disc, so it is located in the 2nd section of the ladder network. Also, the 472nd turn is on the 24th disc, which can be considered in the 5th section of the ladder network modeling.

With regard to the frequency range, this paper has considered the interval between 10 kHz and 1 MHz because this range reflects the geometrical and physical condition of the winding, and the core has a negligible effect on the shape of the FRA at high frequencies (e.g., frequencies above 10–20 kHz [11]).

Furthermore, whereas time is a concern when diagnosis is the objective, time is not important when the objective is modeling and parameter determination. Therefore, time is not a concern in this paper.

In total, the proposed method has six main benefits as follows.

1) This method is simple compared to other analytical modeling methods, which require many calculations.
2) This method provides better matching with measurement results than those provided by other approaches in recent publications [1]–[3], [9], [23].
3) The method can determine the model parameters even if no data are available for the geometrical lengths and the physical information on the inside of a transformer.
4) This method uses the smallest ladder network that can cover all resonance points in the FRA with an EF that is considerably lower than the EFs obtained in other papers.
5) The method reaches to a lower amount of EF in comparison to other methods which consider the same elements with equal values for different sections.
6) This method not only is applicable to homogenous structures, but can also be applied to nonhomogenous winding structures.

The 3-D diagram of Fig. 2 and its internal hidden resonances are quite interesting. The harmony and discipline in the resonance orders presented in Table I need more exploration in the future. Fig. 10 displays a new 3-D diagram for more clarification and verification of the proposed ideas. From the different simulations and practical tests, one can deduce that in the disc-type cylindrical windings, if the measured input impedance in a certain frequency range has N peaks, called dominant or apparent resonances, then this winding will also have exactly $N-1$ hidden peaks. Fig. 10 shows the FRA results for another transformer modeling simulated in MATLAB and having six sections. As Fig. 10 reveals, three salient resonances—R1, R3, and R5—on the curve of the input impedance exist between the 6th section and the ground plotted in the 6th part of the Y-axis $(j=6)$. In addition, the internal impedance measurements between the jth section and the ground $(j=1,\ldots,5)$ produce two more resonances R2 and R4 called hidden, internal, or nondominant resonances.

The best method to verify the number of hidden resonances is a mathematical method. However, this paper is based on experimental and simulation studies. We have used measurements to show the real transformer behavior, and simulations to verify the proposed method. Different simulation and experimental tests were carried out in our lab. All tests showed the same result for the number of hidden resonances. When we accessed the internal points, then we could observe $N-1$ (noticeable) hidden resonances, for N apparent resonances in the terminal

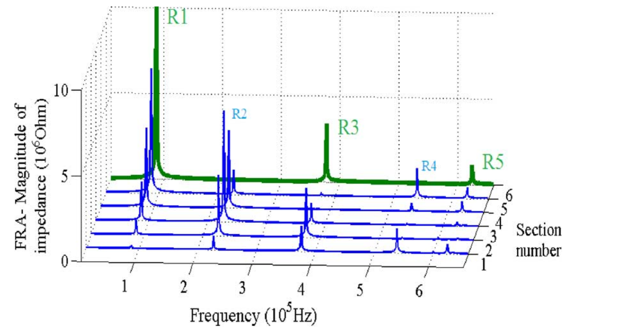


Fig. 10. FRA simulation results: the input impedance between the jth section and the ground (for $j=1,\ldots,6$).

FRA. Each hidden resonance was located between two adjacent apparent resonances. Furthermore, we performed different tests (using an oversized number of sections, for example, 8-section, 10-section, and 19-section ladder network models) based on the proposed methods. Our tests showed that the use of an oversized number of sections (e.g. 19-section network) dramatically complicated the process because the number of unknown parameters and constraints was very high.

To achieve simplicity and accuracy, the best result for fitting the measured and simulated terminal FRAs can be obtained by setting the number of sections to be either equal to $2N-1$ or approximately equal. In this paper, the main objective was to propose a simple model with a minimum number of sections but with acceptable accuracy. In other words, the model used in this paper is not oversized and has a reasonable number of sections.

X. Conclusion

This paper proposed a novel approach for finding an accurate model for transformer windings. The proposed approach was applied to four different cases, and the comparisons between them demonstrated that the nondominant resonances of the FRA test of a transformer were significant. Based on the number of the dominant resonance N and the nondominant resonances $N-1$, the authors developed an equivalent ladder-network model with "$2N-1$" sections to cover all resonances and achieve acceptable accuracy. An optimization algorithm was utilized to find the best solution for covering the measured FRA tests. In addition, the comparison between the FRA simulations and measurements of the four cases illustrated that the most accurate result was for a ladder network model with $2N-1$ sections and with different values for the similar elements of the different sections.

Finally, the major and minor contributions of this paper are as follows.

1) Introducing the hidden resonances concept in order to provide better modeling and more accurate results than those of other approaches.
2) Applying terminal measurements to find the number of dominant resonances, that is, N, and then suggesting a $2N-1$ section ladder network, which can predict the behavior of the winding with acceptable accuracy and by using the minimum number of sections.

3) Using an algorithm to determine the parameters of the $2N-1$ section network based on the real transformer's constraints. The proposed model can have similar or different values for all sections of the ladder network, so this method can be applied to homogenous and inhomogenous windings, which are both used in the industry.
4) Minor contribution: Using (5) instead of the traditional one [(4)], in order to accelerate the parameter determination algorithm and weigh the role of the resonance regions in the defined error function (EF)
5) Minor contribution: Use (13) instead of using the constraints of (7)–(12) to provide high convergence speed and simplify the development of the program.

REFERENCES

[1] T. Y. Ji, W. H. Tang, and Q. H. Wu, "Detection of power transformer winding deformation and variation of measurement connections using a hybrid winding model," *Elect. Power Syst. Res.*, vol. 87, pp. 39–46, 2012.

[2] P. Mukherjee and L. Satish, "Construction of equivalent circuit of a single and isolated transformer winding from FRA data using the ABC algorithm," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 963–970, Apr. 2012.

[3] A. Shintemirov, W. J. Tang, W. H. Tang, and Q. H. Wu, "Improved modeling of power transformer winding using bacterial swarming algorithm and frequency response analysis," *Elect. Power Syst. Res.*, vol. 80, no. 9, pp. 1111–1120, 2010.

[4] K. Ragavan and L. Satish, "Construction of physically realizable driving-point function from measured frequency response data on a model winding," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 760–767, Apr. 2008.

[5] K. Ragavan and L. Satish, "Localization of changes in a model winding based on terminal measurements: Experimental study," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1557–1565, Jul. 2007.

[6] V. Rashtchi, E. Rahimpour, and E. Rezapour, "Using a genetic algorithm for parameter identification of transformer R-L-C-M model," *Elect. Eng.*, vol. 88, no. 5, pp. 417–422, 2006.

[7] V. Brandwajn, H. W. Dommel, I, and I. Dommel, "Matrix representation of three-phase N-winding transformers for steady-state and transient studies," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 6, pp. 1369–1378, Jun. 1982.

[8] C. Arturi, "Transient simulation and analysis of a three phase five-limb step-up transformer following an out-of-phase synchronization," *IEEE Trans. Power Del.*, vol. 6, no. 1, pp. 196–207, Jan. 1991.

[9] P. Vaessen, "Transformer model for high frequencies," *IEEE Trans. Power Del.*, vol. 3, no. 4, pp. 1761–1768, Oct. 1988.

[10] A. Morched, L. Marti, and J. Ottewangers, "A high frequency transformer model for the EMTP," *IEEE Trans. Power Del.*, vol. 8, no. 3, pp. 1615–1626, Jul. 1993.

[11] G. B. Gharehpetian, H. Mohseni, and K. Moller, "Hybrid modeling of inhomogeneous transformer windings for very fast transient overvoltage studies," *IEEE Trans. Power Del.*, vol. 13, no. 1, pp. 157–163, Jan. 1998.

[12] N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "Exploring possibilities for characterization of power transformer insulation by frequency response analysis (FRA)," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1375–1382, Jul. 2006.

[13] N. Abeywickrama, "Effect of Dielectric and Magnetic Material Characteristics on Frequency Response of Power Transformers," Ph.D. dissertation, Dept. Mater. Manuf. Technol., Chalmers Univ. of Technol., Gothenburg, Sweden, 2007.

[14] M. Florkowski and J. Furgal, "Detection of transformer winding deformations based on the transfer function measurements and simulations," *Meas. Sci. Technol.*, vol. 14, no. 11, pp. 1986–1992, 2003.

[15] A. Shintemirov, W. H. Tang, Z. Lu, and Q. H. Wu, "Simplified transformer winding modeling and parameter identification using particle swarm optimizer with passive congregation," *App. Evol. Comput.*, vol. 4448, Lect. Notes Comput. Sci., pp. 145–152, 2007.

[16] A. Shintemirov, W. H. Tang, and Q. H. Wu, "A hybrid winding model of disc-type power transformers for frequency response analysis," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 730–739, Apr. 2009.

[17] S. M. H. Hosseini, M. Vakilian, and G. B. Gharehpetian, "Comparison of transformer detailed models for fast and very fast transient studies," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 733–741, Apr. 2008.

[18] H. Sun, G. Liang, X. Zhang, and X. Cui, "Modeling of transformer windings under very fast transient overvoltages," *IEEE Trans. Electromagn. Compat.*, vol. 48, no. 4, pp. 621–627, Nov. 2006.

[19] M. Popov, L. van der Sluis, R. P. P. Smeets, and J. L. Roldan, "Analysis of very fast transients in layer-type transformer windings," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 238–247, Jan. 2007.

[20] P. Karimifard, G. B. Gharehpetian, and S. Tenbohlen, "Localization of winding radial deformation and determination of deformation extent using vector fitting-based estimated transfer function," *Eur. Trans. Elect. Power*, vol. 19, no. 5, pp. 749–762, Jul. 2009.

[21] P. Karimifard, G. B. Gharehpetian, A. J. Ghanizadeh, and S. Tenbohlen, "Estimation of simulated transfer function to discriminate axial displacement and radial deformation of transformer winding," *COMPEL: Int. J. Comput. Math. Elect. Electron. Eng.*, vol. 31, no. 4, pp. 1277–1292, 2012.

[22] M. Agha-Mirsalim, *Electrical Machines and Transformers*. Tehran, Iran: Prof. Hesabi Publ., 2000.

[23] E. Rahimpour, V. Rashtchi, and H. Shahrouzi, "Applying artificial optimization methods for transformer model reduction of lumped parameter models," *Elect. Power Syst. Res.*, vol. 84, pp. 100–108, 2012.

[24] K. F. Man, K. S. Tang, and S. Kwong, "Genetic algorithms: Concepts and applications," *IEEE Trans. Ind. Electron.*, vol. 43, no. 5, pp. 519–534, Oct. 1996.

[25] Wayne Kerr Electronics Co., Technical data sheet of precision impedance analyzers, Oct. 2008, Issue B. [Online]. Available: http://www.waynekerrtest.com/global/html/products/impedanceanalysis/6500B.htm

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