Valuable Tips for Transformer Ladder Network Parameters Estimation

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***Abstract*—Estimation of the parameters of a transformer ladder network model based on the measured impedance frequency response (IFR) faces major challenges. Nonlinear nature of the system, mutual interaction, frequency dependency of the elements and the number of parameters are those that make the accurate and valid model estimation task involved. In this respect, based on the transformer physical insight, certain tips are derived which contract the search space, suggest the number of the ladder network model sections, provide appropriate initial conditions those improving the performance of the genetic nonlinear optimization algorithm. For the transformer model to be accurate for transient behavior analysis, a 19-section ladder-network model with frequency dependent elements (except capacitors) is considered. The model is modified by adding in-between sections capacitors. The estimation results indicate that while both models succeed in simulating precisely the dominant resonances, the non dominant resonances are better captured by the modified ladder network model.**

Keywords- Transformer; ladder network model; transfer function; impedance frequency response (IFR) ; Error function

I. INTRODUCTION

Study of the transient behaviour of a transformer requires an accurate model. In this respect, transfer function, RLC network, single-phase transmission line (STL), multi conductor transmission line (MTL), ladder network and detailed model are often used [1-2]. The choice of the model largely depends on the intent application.

Parameters of the transfer function is estimated and then, it is used as a versatile tool for the transient behaviour analysis, however, it is an input output relation and does not provide details of the internal conduct of the device [1]. In RLC transient model, a few RLC branches are paralleled, which give accurate modelling at certain frequencies and has lack of precision at the others. This is improved using more branches. The other models are STL and MTL, which are well known methods in transient studies [2]. STL does not take into account the mutual inductances but MTL does. Hence, its accuracy is better than STL. The detailed model, which is developed, based on the transformer physical structure [6] has gained a lot of attention for the study of high frequency behaviour of transformers. The equivalent lumped circuit or ladder network is another model comprising a few sections of circuit each with series and ground capacitances, resistors and self and mutual inductances. The considered model is more accurate when the number of sections is increased. Increase in the number of sections adds the number of parameters and complicates the process of the parameter estimation. Therefore, setting a balance between the accuracy and the dimensions of the problem is required.

Reference signal used for the calculation of the parameters of the model may be the winding impedance frequency response (IFR), which can be recorded using an impedance analyser device. The process of estimation of the model parameters is a nonlinear optimization problem with all of its problems especially when a large number of parameters are involved. Structure of the model and optimization algorithm is two main identification variables. In this respect, using the conventional ladder network model and the evolutionary algorithms has been reported in [6-9]. Greedy optimization search has also been employed in [14].
In this paper, a new ladder network model is proposed and important tips are suggested which accelerates the optimization search toward the optimum parameters values. Moreover, the frequency dependency of the elements is considered. It is shown that the estimated model IFR well follows the measured one so much better than those have already been published.

In Section II, the new ladder network model is exposed. Important tips are discussed in Section III. Experimental study is detailed in Section V and lastly conclusion comes in Section IV.

II. THE NEW LADDER NETWORK MODEL

The ladder network model elements are physically justified, and it can accurately demonstrate the transient behavior of the transformer. In the conventional ladder network model [6-8] shown in Fig. 1, each section contains the series and parallel capacitances (Cs and Cg), self and mutual inductances (L and M_{ij}), series and parallel resistances related to insulation losses (RP and Rg), and ohmic winding resistance (r). Each section of the ladder represents several turns of wire.

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The frequency limitation of the validity of model is in 1MHz range.

The improved model has extra dispersal capacitors (C_d) seated in between the sections as shown in Fig. 1. By comparing the two models, it is realized that the number of parameters has increased and therefore estimation of the parameters gets even more complicated. By this provision it is believed that some dark points in the transformer modeling to be enlighten.

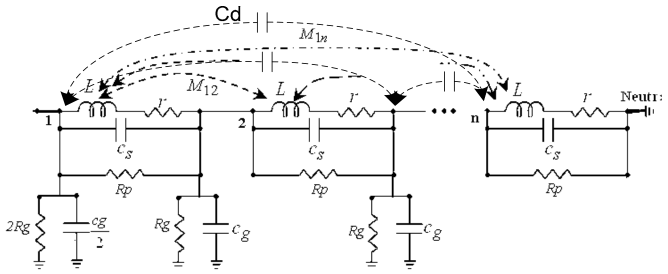


Figure 1. The improved ladder network model

III. TIPS FOR IMPROVING THE LADDER NETWORK MODEL DEVELOPMENT PROCESS

Unfortunately, standards do not suggest any test setup for the model parameter estimation other than at power frequency (50/60Hz) [2]. Hence, three basic methodologies may be pursued:

- Direct calculation based on analytical equations and structure of the transformer.
- Electromagnetic field simulation
- Experimental circuit test

The electromagnetic field simulation and parameter calculation based on winding construction are not typically available except to the transformer manufacturers. The exact direct calculation is not always possible and the approximate one lacks enough information to be reliably used for the transient behavior studies [11].

In the experimental method a feature of transformer such as IFR is measured and a model is fitted to it by using nonlinear optimization method which minimizes a merit of similarity between the actual and the simulated feature [12-13]. In this respect, the ladder network model has been recognized as an effective tool for the intent transformer transient behavior analysis [6]. Unfortunately, estimation of the ladder network model with too many parameters is known to be a difficult task. However, it gets tractable if some constraints derived from the transformer physical insight and employed [6].

A. Constraints for the self and mutual inductances

Consider a winding of N loops where L_{11} is the self-inductance of the first turn and m_{12}, m_{13}, … till m_{1n} are respectively the mutual inductances between the first and two and the first with the other turns. From transformer wiring structure, the following constraints are applicable to the mutual inductances [6]:

$$\begin{aligned}
&0.4L_{i,i} < m_{i,i+1} < 0.85L_{i,i} \quad \forall i = 1,2,....N-1, \\
&0.5m_{i,j-1} < m_{i,j} < 0.95m_{i,j-1} \quad \forall j = 2,3,...N-1 \\
&(m_{ij} - m_{ik}) > (m_{ik} - m_{in}) \;\; \mathit{If} \; |i-j| > |i-k| > |i-n|
\end{aligned} \tag{1}$$

Inequality (1) ensures that the determined structure represents a real transformer model.

B. Initial estimates

In practice an iterative optimization procedure is required to find optimum parameters of the selected model. In any iterative optimization, initial values play a crucial role; therefore, appropriate initials are necessary for the success of the ladder network model estimation. In the following subsections, practical recommendations on selecting initial parameters are introduced.

1) The number of sections

In [1, 6], the number of sections of a ladder network model, larger than twice the number of the resonance frequencies is suggested.

2) Estimation of series resistance

Equivalent resistance of transformer winding can be measured by DC test [2] and also its equivalent AC resistance can be estimated at power frequency. Therefore resistance part of series element in ladder network model can be estimate by dividing the equivalent AC resistance to the number of the sections of the model.

3) Capacitances and insulation resistances

In Section V, it is shown that IFR drastically depends on the choice of Cg and Cs, but it is not too much sensitive to the choice of Rp and Rg from the view point of transient response analysis.

4) Initial estimate for self and mutual inductancest

The following equation is suggested for the model equivalent inductance, L_{eq}, at power frequency [14]

$$L_{eq} = N_{ladder} \times L_{11} + 2 \times \sum_{i=1}^{N_{ladder}-1} (N_{ladder} - i) \times m_{1,i+1} \tag{2}$$

At low frequency, the capacitors of the model are neglected and L_{eq} can be measured directly. N_{Ladder} is the number of sections of the model, L_{11} is the self and $m_{1,i+1}$ is the mutual inductances both at power frequency. Considering (1), the mutual inductances can be expressed as a portion of the self-inductance ($m_{1,2}$=0.8L_{11}, and so on); also, by applying Equation (2), an initial estimate for self and mutual inductances is obtained.

C. Frequency dependency of the parameters

Transformer's behavior is nonlinear and frequency dependent [2]. For the sake of simplicity, often the frequency independent ladder network model has been investigated [6-9]. Here, the effect of using frequency dependent parameters for accurate modeling is investigated. First, the parameters are measured at power frequency (50/60 Hz) and then, based on the existing equations, described later, the frequency dependent curve in Hz-MHz range for the elements are calculated using IFR. The identification is improved as the difference between the measured IFR and the simulated one is decreased.

The general equations expressing the frequency dependency of the elements are as follows:

1) Frequency dependency of inductance matrix

Inductance matrix of the ladder network model contains self and mutual inductances. These inductances decease by raising the working frequency [15]. The equation expressing the relationship is given by,

$$L(f) = A + (1 - A)e^{-B\times f} \quad (3)$$

Which has two unknown parameters, A and B that has to be identified.

2) Frequency dependency of the Insulation Resistance

The insulation resistance of the transformer winding (Rp and Rg) decreases with increasing the frequency (f). In [16], the following equation has been suggested,

$$R = \frac{1}{\tan\delta \times C \times 2\pi \times f} \quad (4)$$

The Frequency dependent of terms $\tan\delta$ and C can be neglected and thus the equation is contracted to,

$$R \propto {}^{1}\!/_{f} \quad (5)$$

3) Frequency dependency of the series Resistance

Series resistance of transformer winding is increased by raising the working frequency. A complicated relationship between r and f has been suggested in [16]. Embarking on this tense equation unnecessarily makes the estimation process more involved [6]. Therefore, it is wise using a more simpler relation as given below [10],

$$r \propto \sqrt{f} \quad (6)$$

As [10] indicates the validity of the model is not disturbed using the alternative simpler equation.

D. Optimization algorithm

1) Error Function

The difference between the reference curves (r) obtained from measurement and simulation results (s) based on the equivalent circuit model is defined as error function [1-2, 6]. Other merits have also been used [1-2, 6]. The percentage error is not a useful index, as often the function gets zero. Instead, either the percentage of the maximum value or the actual error is more favored [1]. By the way, one of the most common used error function (EF) is expressed as below,

$$EF = \frac{\sum_{i=1}^{P} |r_i - s_i|}{P} \quad (7)$$

Where, P is the number of samples of the curve.

2) Optimization Algorithm

Various optimization algorithms have been employed for the estimation of the ladder network model parameters [2, 6, and 14]. A high dimension nonlinear optimization problem is both time consuming, complicated and suffers from local minima. Since using greedy search [14] is impossible, the evolutionary methods such as genetic, ant colony algorithms and neural network [6-9] project themselves as promising choices.

3) Homegenous versus inhomegenous model

Initially, using homogeneous model to start simulation process is suggested; however, if the estimation fails to provide acceptable results, resorting to inhomogeneous model is recommended.

IV. CASE STUDIES

The tests are carried out on a 20kV/0.4kV, 1600kVA power transformer [6] shown in Fig. 3. The input impedance of the high voltage (HV) winding of the transformer is measured using the impedance analyzer device "Wayne Kerr 6500B Precision Impedance Analyzer Series" while the secondary is open circuit.

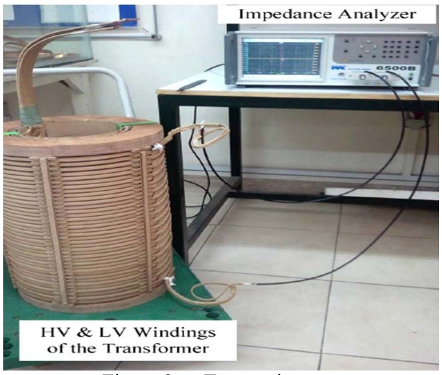
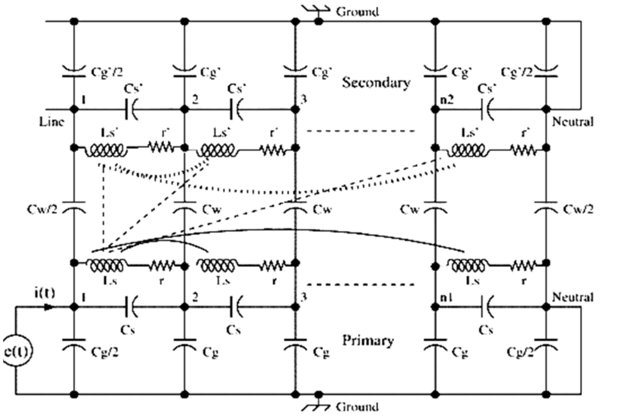


Figure 2. Test equipment

A. Estimation of the ladder network model

The high and low voltage windings of the transformer are modeled as two separate ladder network model of 19 sections as shown in Fig. 3. In the figure the insulation resistances are not shown.

The model parameters of the conventional and the proposed detail model are estimated using Genetic Algorithm (GA). The result has been depicted in Fig. 5. As the graphs indicate both are well capable of modeling the dominant resonances, but the conventional model fails in accurately simulating the non-dominant (cancelled by zeros) resonances. However, this shortcoming is alleviated when the modified model is used.



___ Magnetic coupling between the inductances of primary winding
…… Magnetic coupling between the inductances of secondary winding
---- Magnetic coupling between the inductances of primary and secondary windings

Figure 3. Model for two-winding transformer [10]

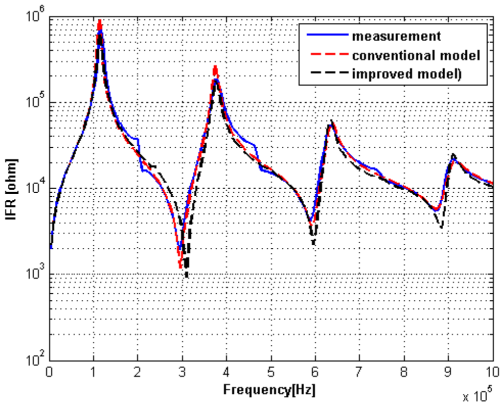


Figure 4. Comparison of the measured IFR versus the simulate ones based on the conventional and the modified models.

While the process of estimating the parameters of the modified model is tenser than those of the conventional model, its capacity in modeling the non dominant (cancelled by zeros) resonances makes it worthwhile.

B. Model validity

It should be mentioned that just the good agreement between the measured and simulated results cannot guarantee the validity of the model as it is discussed in [14]. Fortunately, the disk endings of the test transformer are accessible, and the input impedance from node 2 to 19 with respect to the ground can be measured and used as an index of validity. Two of such measurements and their corresponding estimated ones have been depicted in Fig 5 and 6.

Both figures explicitly exhibit the improvement achieved using the modified model versus the conventional one. Meaning that, the proposed model is a better tool for the assessment of the transformer transient analysis.
Basically the internal endings of the windings are not accessible; therefore, the above validation procedure cannot be pursued. Alternatively, the input impedance of the low voltage side is measured while the HV side is open circuit. A model which presents acceptable match in both cases is considered a valid model.

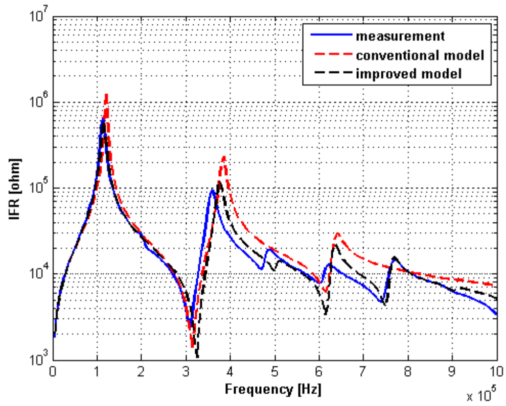


Figure 5. IFR from the node 2

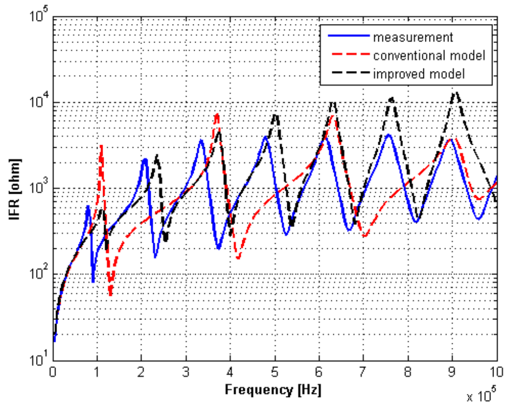


Figure 6. IFR from the node 19

C. Dependency of input impedance versus the parameters

In Section 3, suggestions for the selection of the appropriate initial values for the series resistance, self and mutual inductances are presented. But nothing mentioned about the choice of series and parallel capacitances (C_s and C_g) and parallel resistances related to insulation losses (R_P and R_g). In [18] tips for the values of the series and parallel capacitances (C_s and C_g) are presented. Here, the effect of variation of these parameters on the IFR is evaluated.

Let assume a ±40% tolerance for the Cs, Cg, Rp and Rg parameters. Effect of these variations (Kf factor) has been depicted in Figs 7, 8, 9 and 10. Figure 8 shows false value for C_s, drastically displaces the resonances at frequencies above 250 kHz. On the other hand, incorrect value for C_g, obscures the low frequency components as it has been displayed in Fig. 9. On the other hand, as Fig. 10 exhibits, wrong value for Rp just affects the amplitude and it does not manipulate the location of the resonances. The same is also true for Rg. Meaning that, inaccurate estimation of them does not inflict deranged effect on IFR and does not alter the quality of the model required for the transient analysis.

V. CONCLUSION

In this paper, a new ladder network model for transformers is suggested. Due to the large number of parameters existing in the model, appropriate initial conditions for accurate estimation of parameters are required. It is shown that choice of Cg and Cs has drastic impact on IIFR. The elements of the ladder network model are assumed frequency dependent except the capacitors. The experimental results indicate that the conventional ladder network model can appropriately simulate the dominant resonances, while the modified is capable of modeling both dominant and non dominant (cancelled by zeros) resonances.

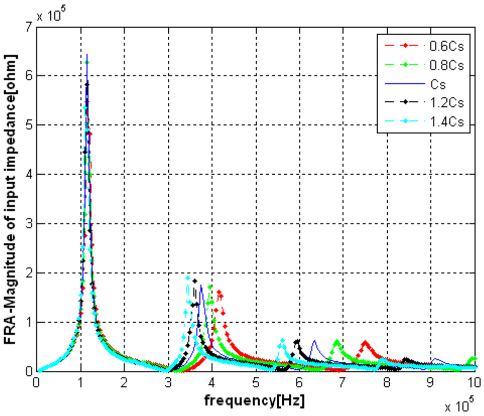


Figure 7. Effect of Cs variations on transfer function

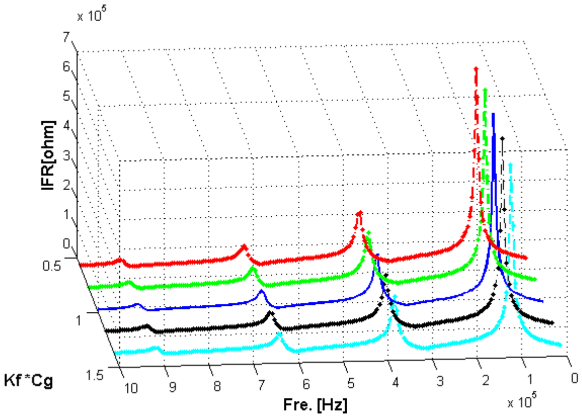


Figure 8. Effect of C_g variations on transfer function

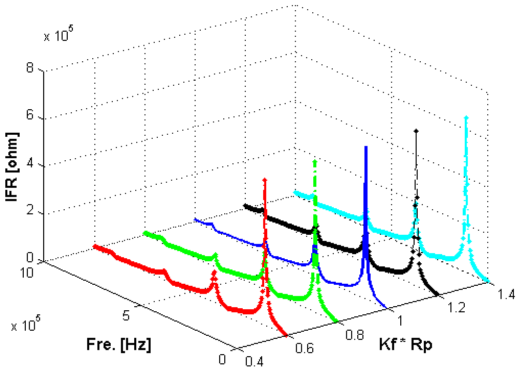


Figure 9. Effect of R_p variations on transfer function

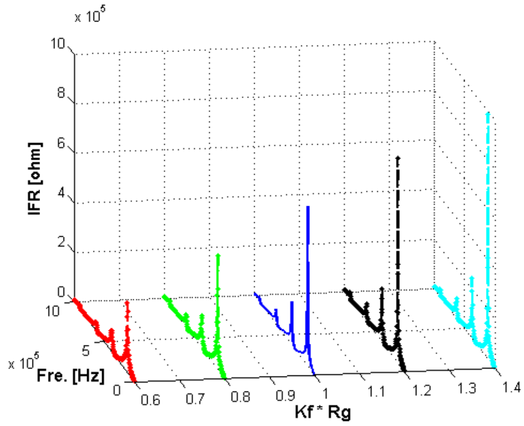


Figure 10. Effect of R_p variations on transfer function

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