Optimal Synthesizing Symmetrical Transformer Winding Network parameters for Monitoring Transformer Operation Using Sweep Frequency Response

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Abstract—Power Transformers are the most considerable and expensive critical element of power network systems. They play a remarkable part in power transmission to the users. They are needed to be continuously and regularly monitored and assessed in order to avoid any catastrophic failure and to increase the reliability of the power supply. The present paper proposes synthesizing technique for the transformer model winding by performing sweep frequency response analysis (SFRA) test.However, the critical challenge is to appropriately interpret the measured response, which remains a gray area left for experts.Experimental terminal measurement, number of pronounced resonances contributed in restricting search span for finding the parametersof the synthesized ladder network using genetic algorithm.Defining voltage distribution constant was the critical key to compute the optimal and rational parameter valueswithin a short time.The designed and manufactured single, isolated,interleaved, air-cored modelwinding was introduced for experimental investigation to the proposed technique.Moreover, the estimated digital simulation of the synthesized circuit and terminalmeasurement results were reported and found to beapproximately same.

Keywords- power transformers, transformer diagnosis, sweep frequency response analysis (SFRA), axial displacement, winding deformation, optimization, genetic algorithm, artificial intelligence.

I.INTRODUCTION

Power transformer is very imperative component in the electrical sub-transmission and transmission network. The transformer reliability is relatively high that can be in service for 20-35 years. The majority of transformers currently in service worldwide and now in service were commissioned before 1975's .The majority of transformers currently in service worldwide in consequence the majority of them have exceeded their validity date and design lifetime[1]. And here comes the importance of SFRA in condition monitoringthe transformer.Sweep frequency analysis approach is a highly sensitive method which has several advantages over other various techniques such dissolved gas analysis method, reactance comparison method and low voltage impulse method [15], The main advantages of the swept frequency method over the other method are:a wider range of frequencies are injected; less signal to noise ratio; less measurement tools are required[9].SFRA technique measures the input impedance or the driving-point impedance (DPI) of transformer windings over a wide frequency range to construct thereference circuit model[2]. The SFRA signature of the transformer is considered as a significant fingerprint and can detect any minor physical modification [3-5].This paper presents a genetic algorithm optimization method to synthesize a transformer equivalent circuit, based on a given direct measurement.

II.FREQUENCY RESPONSE ANALYSIS

The SFRA approach is a highly sensitive technique, which has several advantages over other various diagnostic techniques, such as dissolved gas analysis method, reactance comparison method, and low voltage impulse method [2, 6]. InFigure (1) shows the configuration test to measure input voltage and output current to obtain input admittance or DPI by Keysight Technologies E4980A LCR Meter [7].

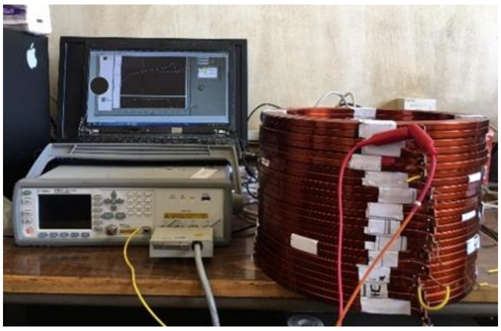

Figure (1):LCR Meter preforming DPI magnitude and phase response 20 Hz – 2 MHz of single continuous winding typeby the author and supported by the Egyptian National Research Center.

When the DPI magnitude inFigure (2) is maximum and the corresponding phase at the same frequency is zero (at change from positive to negative), the certain frequencies in this peak can be called open-circuit natural frequencies (OCNF). When the DPI magnitude is at its minimum and the corresponding phase at the same frequency is zero (at change from negative to positive), the frequencies at these troughs can be called short-circuit natural frequencies (SCNF). Determining OCNF as well as SCNF will help in forming DPI-function of second order poles and zeros [8]. The natural frequencies change if the transformer mechanical integrity has been exposed to any harm[9].

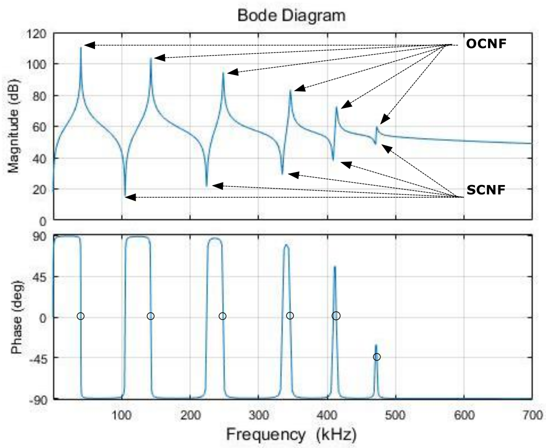

Figure (2):Magnitude and phase of DPI.

III. SYNTHESIZING OF TRANSFORMER LADDER NETWORK MODEL

The transformer physical continuous winding can be visualized by a network of electrical parameters, which are stray capacitance (C_s) between the conductor blocks, ground capacitance (C_g) between conductors and ground (tank or grounded core) as shown inFigure (3).

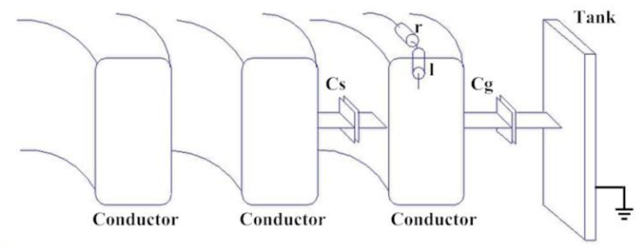

Figure (3): Close view of the conductors and modeled Parameters.

This visualization can be represented by an electrical model circuit of serial discrete nodes, starting from the line end to the neutral end as shown inFigure (4). (l_s) is the self-inductance and in series with the conductor resistance, (r) while (m) is the mutual inductance between two discs. (n) is the number of ladder network section which can be determined by the number of OCNFs [10].

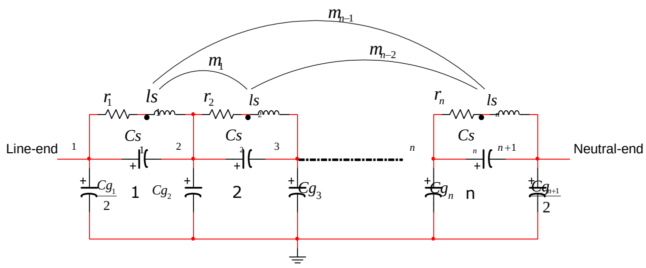

Figure (4): Ladder network model with n network sections.

IV. EXPERIMENTAL SETUP

A fully interleaved isolated air-cored disk model winding was purposely manufactured for SFRA test.The area of the wounded rectangularenameled cupper wire is (2*8) 16 mm squire. This type of wire is often used in distributortransformers and high-power rating.Each disk consists of 15turn. Thedisk inner and outer diameter were240mmand275 mm respectively.The total heightwas 33 mm after stacking four disks with no vertical space considered between disks.the two adjacent disks were connected by soldering flexible copper wires to the disk-ends.The line-end of the model winding was excited with sinusoidal signal with frequency range 20 Hz~20 MHz to grantee all the natural frequencies are being pronounced with its neutral-end grounded.

V. REFERNCE MODEL IDENTIFICATION

Genetic algorithm (GA) can be used to determine ladder network parameters following procedures inFigure (5), as it is very fast convergence, high-quality optimization algorithm [10-15].

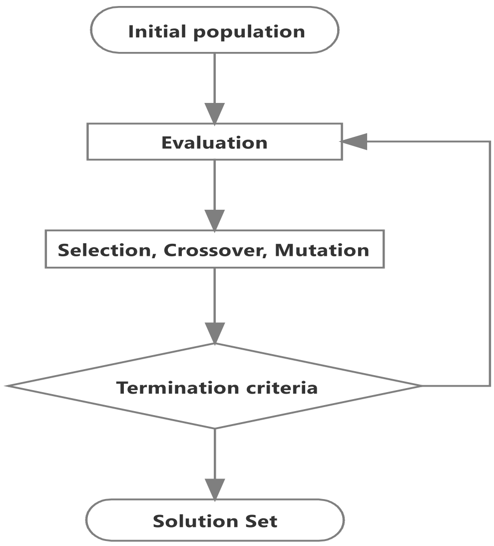

Figure (5):Operational flow of the proposed genetic algorithm

Algorithm1 Reference Model

1- Measuring DC resistance (R_{DC})[8];

2- Measuring equivalent air-core inductance (L_{eq}) [11];
3- Performing SFR test while neutral is grounded to obtain DPI;
4- Determining the number of OCNFs (q) and SCNFs $(q-1)$ of the model winding by swept frequency measurements;
5- Determining the number of OCNFs (q) and SCNFs $(q-1)$ of the model winding by swept frequency measurements;
6- Determining the number of sections (n) of the equivalent circuit to be synthesized [8];

$$n \leftarrow q \qquad (1)$$

7- Constructing resistance diagonal matrix $[R_{ref}]$ with diagonal element $\left(\frac{R_{DC}}{N}\right)$[13];

$$R(i,i) = r, \qquad 1 \le i \le n \qquad ()$$

$$[R] = \begin{bmatrix} r_1 & 0 & \dots & 0 \\ 0 & r_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & r_n \end{bmatrix}$$

8- Determining of the search ranges of $(l_s, m_1, m_5, \dots, m_{N-1})$ considering the following constraints [13]:

$$0.3\,\frac{L_{eq}}{n} \le l_s \le 0.5\,\frac{L_{eq}}{n} \qquad (2)$$

$$0.4\, l_s < m_1 < 0.8\, l_s \qquad (3)$$

$$0.4\, m_{i-1} < m_i < 0.8\, m_{i-1}, \forall i = 2, \dots, n-1 \qquad (4)$$

9- Constructing inductance matrix $[L_{ref}]$;

$$[L_{ref}] = \begin{bmatrix} l_1 & m_1 & m_2 & \dots & m_n \\ m_1 & l_2 & m_1 & \dots & m_{n-1} \\ \vdots & \vdots & \ddots & \dots & \vdots \\ m_{n-1} & m_{n-2} & m_{n-3} & \ddots & \vdots \\ m_n & m_{n-1} & m_{n-2} & \dots & l_n \end{bmatrix} \qquad (5)$$

10- Estimating voltage distribution constant (α) range from similar design details and compute the search range of C_s.

$$C_g = \frac{C_{g,eff}}{N} C_g = \frac{C_{g,eff}}{n}; \qquad (6)$$

$$C_{s,min} = \frac{N \times C_{g,eff}}{\alpha^2_{min}}; \quad C_{s,max} = \frac{N \times C_{g,eff}}{\alpha^2_{max}}; \qquad (7)$$

11- Constructing and represent node capacitance matrix $[K_{ref}]$;

$$[K_{ref}] = \begin{bmatrix} C_{s_1} + \frac{C_{g_1}}{2} & -C_{s_1} & \dots & 0 \\ -C_{s_1} & C_{s_1} + C_{g_2} + C_{s_2} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & -C_{s_{n-1}} & C_{s_{n-1,n}} + C_{g_n} \end{bmatrix} \qquad (8)$$

12- Applying all of this aforementioned information to ladder network state space model and GA toolbox in MATLAB to obtain winding parameters values that produces highly correlated simulated DPI to the measured one by minimizing the GA objective function (OF) [14].

$$OF = \frac{\sum_{i=0}^{P} w_i \cdot \sqrt{\left[\frac{s_i + \left(\frac{s_i + r_i}{2}\right)}{\frac{s_i + r_i}{2}}\right]^2 + \left[\frac{r_i + \left(\frac{s_i + r_i}{2}\right)}{\frac{s_i + r_i}{2}}\right]^2}}{\sum_{i=0}^{P} w_i} \qquad ()$$

Where P is the number of points. w_i is the weight factor of point i. r_i is the measured point and s_i is the simulated point

VI. CASE STUDY AND SIMULATION

In this case, the reference circuit model is built based on terminal measurement of some quantities such as DC resistance, equivalent air-core inductance, natural frequencies from DPI, and initial voltage distribution constant range for similar designs. Assuming all the self-inductances (L_s), mutual inductances of $(M)_{ji}$ and $(M)_{ij}$, ground capacitance (C_g) and series capacitance $(C)_s$ for all network are identical.

$$R_{DC} = 0.02\,\Omega, \quad L_{eq} = 1.095\ mH, \quad \alpha_{min,max} = 1.4\sim2.2$$

The GA variables of upper and lower limits have been tabulated in TABLE I, which are ground capacitance and stray capacitances.

TABLE I. Estimated Parameter Values of The Reference Model

Parameters	GA lower limit	GA upper limit	GA estimation
C_g	0.0001	10	0.098

C_s	0.0001	10	0.0367

*VII.*RESULTS

From the GA parameter estimation in TABLE I as well as the parameters that have been determined by terminal measurements. GA obtains the optimalparameters value by minimizing the objective function whichis pertaining to the correlation and deviation of the measured and simulated. DPI.GA toolbox options is listed in TABLE II.**GA Options**

TABLE II.GA Options

Parameter	Value
Population type	Double Vector
Population Size	50
Scaling Function	Rank
Selection Function	Stochastic Uniform
Initial Penalty	10
Penalty Factor	100
Generations	400

The range of α winding model to similar designs, was the only constraint that has been considered to give the desired optimal parameter values. The GA algorithm convergence time for obtaining the solution was less than 5 minutes.The estimated DPI plot (blue line) is produced nearly same as actual DPI plot (red line) with best fit value 0.04 in Figure (6).

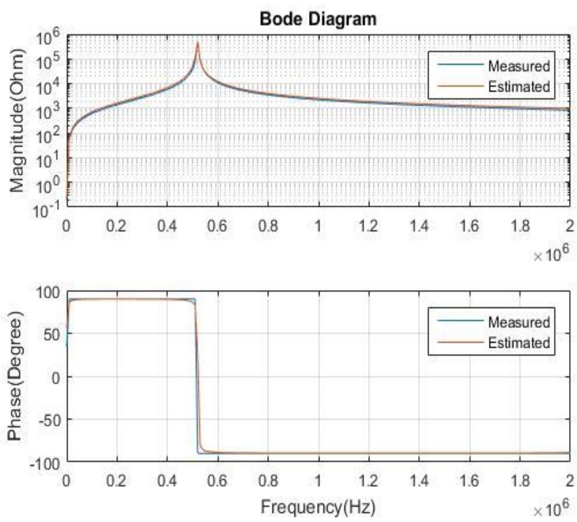

Figure (6):Comparison of actual DPI magnitude and phase and the estimated DPI from synthesized ladder network obtained by GA.

*VIII.*CONCLUSION

In this paper work, GA is fed by the acquired terminal measurement to synthesize transformer reference circuit model. Initial voltage distribution constant was dominantly effective in converging computing time and OF error.With the help of fitness function, the variables such as ground capacitance, series-capacitance are estimated. Furthermore. The GA estimated parameters approximately equal to the experimental for both cases with very acceptable time efficiency and error.

*IX.*ACKNOWLEDGMENT

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