Novel approach for a ladder network model of the transformer winding high-frequency parameters identification based on FRA data

Abdallah Chanane[1], Messaoud Belazzoug[1]

[1]Laboratoire des systèmes électriques et télécommande, Faculté de Technologie, Université Blida1, BP 270, route de Soumaa, Blida, Algeria.

chanane.abdallah@gmail.com,m_belazzoug@yahoo.fr

Corresponding author: chanane.abdallah@gmail.com

chanane.abdallah@univ-blida.dz

Abstract

The identification of the high-frequency ladder network model (LNM) parameters for the transformer winding is the way to confirm its actual condition. This paper aims to present the application of one of the latest approach algorithms, namely, Particle Swarm Optimization with Invasive Weed Optimization (PSO-IWO) method for the identification of the high frequency LNM parameters for the transformer winding. The physical realizability of the LNM is ensured and it is based on the frequency response analysis FRA data and some terminal measurements of a transformer winding. The results are agreement and indicate that the identified model, is superior in terms of representing the physical behavior of the transformer winding in high frequency.

Keywords

Identification, Transformer winding, Diagnosis, equivalent circuit, PSO-IWO

Introduction

Power transformer is one of the most expensive equipment in a power system. Transformers practice excessive faults during exploitation, and this disturb the quality and the continuity of service. For this motive, diagnosis is necessary. Several procedures have been developed for diagnosis such as vibration analysis [1], [2], transfer function (TF) [3], [4] and frequency response analysis (FRA) [5], [6].

The FRA is one of the best technique that can detect even the slightest changes in the transformer winding [7], [8]. Even so, pertaining FRA practice requires consistent interpretation methods including finite element modelling (FEM), mathematical models, analytical approaches, numerical indices and TF as reported in [6], [8], [9].

Nowadays, intelligent algorithms have been used to identify the LNM and to offer a global solution, such as genetic algorithm, particle swarm optimization, crow search and simulated annealing algorithms [10], [11] bacterial swarming [12], neural network [13], Grey Wolf [14] and bat algorithm [15]. In this paper, a novel approach is applied to identify the high-frequency parameters transformer winding using the PSO-IWO algorithm. The proposed algorithm uses the IWO method as a local search tool to improve the convergence and the characteristics of PSO in fast calculation. The proposed LNM is mutually coupled and physically realizable. Identification of the model parameters is presented and the results are validated through a case study of a transformer winding.

1. Proposed LNM

The transformer winding can be modeled by considering a mutually coupled LNM with N-section as shown in the Figure 1. The parameters of the LNM are defined as follows: N is the number of sections, r is the resistance per section, C_g is the capacitance to the ground per section, C_S is the series capacitance per section, L_s is the self-inductance and M_{IN} is the mutual inductances between different cells.

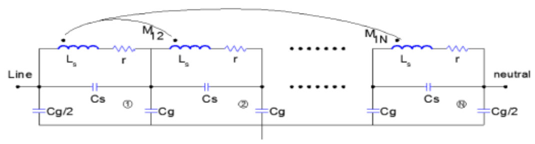

Fig. 1 *Equivalent circuit of a transformer winding*

- Capacitance matrix:

The total shunt capacitance (C_{geff}) and the ground capacitance per section (C_g) are, respectively, estimated according to the equations (1) and (2) [4], [14]:

$$C_{geff} = C_s . Q^2 / N \quad (1)$$

$$C_{gi} = C_g / N \quad (2)$$

Where: Q is the voltage distribution constant.

The equivalent capacitance of the LNM (C_{eq}) is estimated according to equation (3):

$$C_{eq} = \frac{C_{gi}}{2} + \frac{1}{\frac{1}{C_s} + \frac{1}{C_{gi} + \frac{1}{\frac{1}{C_s} + \cdots}}} \quad (3)$$

- Inductance matrix

One of the physical properties of the transformer winding is that the magnetic coupling decreases when the distance between the discs increases [4], [6]. Consequently, the self and the mutual inductances could be limited between two bounds (upper and lower bounds) as given in equations (4) and (5):

$$0.1\ L_{ij} < M_{ij} < 0.9\ L_{ij} \qquad (4)$$

$$0.10 M_{ij} < M_{ij+1} < 0.99 M_{ij}\ ,\ i, j = 1\ \ldots\text{where}, i \neq j$$

$$\text{and}\ \ L_{ij} > M_{12} > \ldots > M_{ij} \qquad (5)$$

The total equivalent inductance of the model winding could be expressed as per equation (6):

$$L_{eq}(\text{estimated}) = NL_i + 2\sum_{i=1}^{N-1}(N-1)M_{i,i+1} \qquad (6)$$

2. Proposed PSO-IWO method

2.1 PSO Algorithm

This algorithm is one of the stochastic algorithms [16]. By the way, novel concepts were developed such as the convergence rate and the selected parameters as reported in [17], [18], [19]. The position of the particle is calculated according to the individual's best and the group's best experience of the particle swarm. Each particle represents an achievable solution to the problem [18], [19].

2.2 IWO algorithm

The IWO is a stochastic algorithm inspired from the colonization of invasive weeds [20]. The algorithm starts randomly, then, members of the population produce seeds based on their comparative fitness in the population. The convergence rate and the selected parameters are reported in [20].

3.3 Hybrid PSO-IWO algorithm to identify the LNM

For a better solution quality, two algorithms are combined, in which, fully-guided movements for each iteration good exploration are ensured by PSO and IWO method respectively. This choice avoids some drawbacks such as being trapped in local optima or converging to global optima in a long time.

Reference value [4]	Frequency peaks (F_{Pi})						ΔF_{Pi}
	1st	2nd	3nd	4nd	5nd	6nd	
	40.48	142.58	249.42	346.41	414.34	473.73	
PSO-IWO	40.77	142.30	249.20	346.00	414.20	473.00	0.5917
CSA[11]	40.1	142.30	248.5	344.70	414.20	477.6	2.8100
Reference value [4]	Frequency Troughs(F_{Ti})						ΔF_{Pi}
	1st	2nd	3nd	4nd	5nd	-	
	105.19	224.79	334.44	410.09	472.42	-	
PSO-IWO	104.9	224.5	334.00	409.50	471.00	-	0.9830
CSA[11]	104.9	223.8	332.7	409.5	475.6	-	2.0400
$\Delta F_i = \frac{\sum \text{Reference values} - \sum \text{Estimated values}}{\sum \text{Reference values}} x100$							

Table. 2 Comparison of the reference and the estimated frequencies

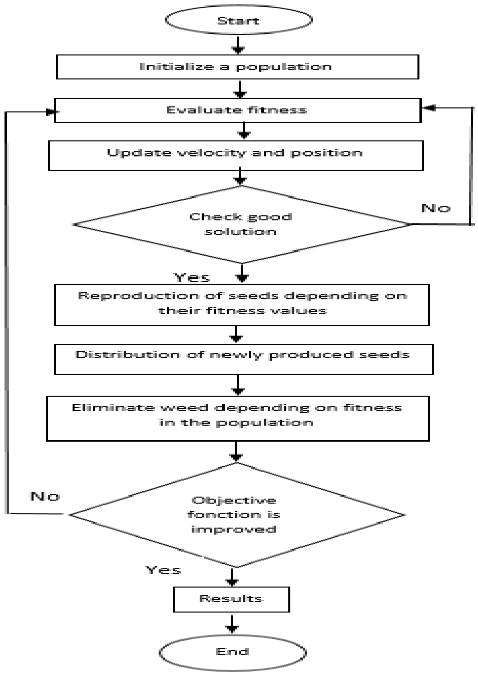

Fig. 2. *Flowchart of the PSO-IWO algorithm*

3. Implementation of the PSO-IWO to identify the LNM Parameters

FRA measurements were performed on the model of winding [4], in which the physical parameters are given as follow; the total inductance and effective capacitance were equal to 6.98mH and 5.6nF respectively. The total resistance was equal to 8Ω. An iterative algorithm was used to estimate the parameters of the involved electrical equivalent circuit. Finally, the FRA signature is obtained through the synthesized electrical equivalent circuit [4]. To identify the LNM of the transformer winding, the obtained results are compared to with those obtained by [11].

Parameters	Reference value (reprinted from [4])	PSO-IWO	CSA[11]	Deviation from the reference (%) $DEV = \frac{100}{N} \times \left\lvert\frac{Reference - identified}{Reference}\right\rvert$	
				PSO-IWO	CSA
Ls (mH)	0.4310	0.4310	0.4307	0.0	0.01
M1 (mH)	0.2392	0.2390	0.2390	0.013	0.138
M2 (mH)	0.1435	0.1430	0.1429	0.056	0.068
M3 (mH)	0.0947	0.0945	0.0949	0. 011	0.035
M4 (mH)	0.0612	0.0613	0.0610	0.026	0.053
M5 (mH)	0.0496	0.0497	0.0492	0.033	0.133
C_S (nF)	0.600	0.601	0.59	0.026	0.276
C_{eq}(nF)	0.8819	0.8824	0.8765	0.00	0.101
α	7.48	7.47	7.54	0.0223	0.021
L_{eq}(mH)	7.0385	7.0316	7.0292	0.0163	0.021

Table. 1 Comparison of the reference and the identified parameters of the LNM

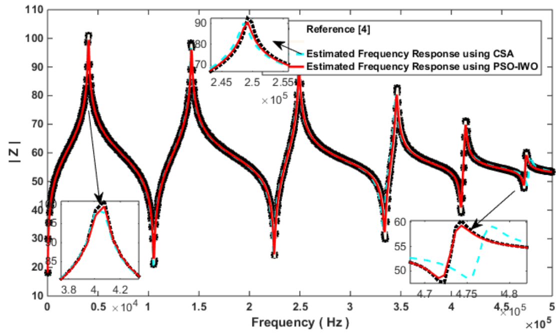

Fig. 3. *FRA curves of the model winding*

Discussion:

The proposed Ladder Network Model presents the physical behavior of the transformer winding. The proposed PSO-IWO method present serval advantages, mainly:

- The best exploration and exploitation search. Thereby, the global best solution always directed to a better position, as the algorithm proceeds.
- A luxurious, time-efficient and a flexible computation is verified, the effectiveness of PSO-IWO was tested by the Crow Search Algorithm.

conclusion

This paper has presented a novel approach based on PSO-IWO to identify the parameters of a Ladder Network Model of a transformer winding. The case study presented in previous sections suggest the capability of the PSO-IWO method for the construction of the LNM of a transformer winding. Through the case study, it has shown that the proposed PSO-IWO is good in terms of accuracy and effectiveness, since the proposed method is compared with other reported in the literature. The obtained results are very promising and prove the efficiency and the high solution quality.

Acknowledgment

The authors would like to thank the Directorate General for Scientific Research and Technological Development, Algeria (Direction Générale de la Recherche Scientifique et du Développement Technologique “DGRSDT”, Algerie), for the resources provided for scientific research and development.

References

[1] Hong, K., Huang, H. and Zhou, J. (2015), “Winding condition assessment of power transformers based on vibration correlation”, IEEE Transactions on Power Delivery, Vol. 30 No. 4, pp. 1735-1742.
[2] Seo, J., Ma, H. and Saha, T.K. (2017), “A joint vibration and arcing measurement system for online condition monitoring of onload tap changer of the power transformer”, IEEE Transactions on Power Delivery, Vol. 32 No. 2, pp. 1031-1038.
[3] Mukherjee, P. and Satish, L. (2012), “Construction of equivalent circuit of a single and isolated transformer winding from FRA data using the ABC algorithm”, IEEE Transactions on Power Delivery, Vol. 27 No. 2, pp. 963-970.
[4] Ragavan, K., Satish, L.: ‘Localization of changes in a model winding based on terminal measurements: experimental study’, *IEEE Trans. Power Deliv.*, 2007, **22**, (3), pp. 1557–1565
[5] Alsuhaibani, S., Khan, Y., Beroual, A. and Malik, N.H. (2016), “A review of frequency response analysis methods for power transformer diagnostics”, Energies, Vol. 9 No. 11, p. 879
[6] Pramanik, S. and Satish, L. (2011), “Estimation of series capacitance of a transformer winding based on frequency-response data: an indirect measurement approach”, IEEE Transactions on Power Delivery, Vol. 26 No. 4, pp. 2870-2878.
[7] Liu, Y., Ji, S., Yang, F., *et al.*: ‘A study of the sweep frequency impedance method and its application in the detection of internal winding short circuit faults in power transformers’, *IEEE Dielectr. Electr. Insul. Soc.*, 2015, **22**, (4), pp. 2046–2056
[8] Samimi, M., Tenbohlen, S.: ‘FRA interpretation using numerical indices: state-of-the-art’, *Electr. Power Energy Syst.*, 2017, **89**, pp. 115–125
[9] Liu, S., Liu, Y. A L. H. and Lin, F. (2016), “Diagnosis of transformer winding faults based on FEM simulation and on-site experiments”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 23 No. 6, pp. 3752-3760.
[10] Chanane, A., Bouchhida, O., Houassine, H.: ‘Investigation of the transformer winding high-frequency parameters identification using particle swarm optimisation method’, *IET Electr. Power Appl.*, 2016, **10**, (9), pp. 923–931
[11] Chanane, A., Houassine, H. and Bouchhida, O. (2019), “Enhanced modelling of the transformer winding high frequency parameters identification from measured frequency response analysis”, IET Generation, Transmission and Distribution, Vol. 13 No. 8, pp. 1339-1345.
[12] Shintemirov, A., Tang, W. A T. W. and Wu, Q. (2010), “Improved modelling of power transformer winding using bacterial swarming algorithm and frequency response analysis”, Electric Power Systems Research, Vol. 80 No. 9, pp. 1111-1120.
[13] Zambrano, G., Ferreira, A. and Caloba, L. (2006), “Power transformer equivalent circuit identification by artificial neural network using frequency response analysis”, IEEE Power Engineering General Meeting, Montreal, Canada, No. 11, pp. 1-6.
[14] Abdallah Chanane, M. Belazzoug, ‘ On accuracy of a mutually coupled ladder network model high-frequency parameters identification for a transformer winding using gray wolf optimizer method’, Computer Science Compel-the International Journal for Computation and Mathematics in Electrical and Electronic Engineering Vol. 40 No. 1, pp. 40-50.
[15] Sahnoune Chaouche, M., Houassine, H., Moulahoum, S., *et al.*: ‘BA to construction of equivalent circuit of a transformer winding from frequency response analysis measurement’, IET Electric Power Applications, vol-12, pp-728-736.
[16] Kennedy, J., Eberhart, R.C.: ‘Particle swarm optimization’. Proc. IEEE Int. Conf. on Neural Networks IV, Perth, Australia, 1995, pp. 1942–1948
[17] Trelea, I.: ‘The particle swarm optimization algorithm, convergence analysis and parameter selection’, Inf. Process. Lett., 2003, **6**, (85), pp. 317–325
[18] Shi, Y., Eberhart, R.C.: ‘Empirical study of particle swarm optimization’. Proc. of the Congress on Evolutionary Computation, Washington D.C., USA, 1999, pp. 1945–1950
[19] Clerc, M., Kennedy, J.: ‘The particle swarm explosion, stability, and
convergence in a multidimensional complex space’, IEEE Trans. Evol.Comput., 2002, **6**, pp. 58–73
[20] Mehrabian, A.R., Lucas, C.:’ A novel Numerical Optimization Algorithm Inspired from Weed Colonization’, Ecological Informatics, 2006,(1), pp. 355-366.

Artificial intelligence