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Partial discharge detection in transformer winding using FRA analysis

***Abstract**. In power transformer, Partial Discharge is a cause of insulation failure, and thus, procedures for the area of PD sources are required. In this paper, an endeavor has been made to present* frequency response analysis *(FRA) for the discovery of PD by identifying the parameters of the winding by the* particule swarm optimization *(PSO), and giving its impedance according to the frequency. Comparison between the frequency responses of healthy winding and the affected one the is made to detect the failure associate to the partial discharge.*

Streszczenie.** W transformatorach energetycznych wyładowania niezupełne są przyczyną uszkodzeń izolacji, dlatego konieczne jest opracowanie procedur wykrywania źródeł wyładowań niezupełnych. W niniejszym artykule podjęto próbę przedstawienia analizy odpowiedzi częstotliwościowej (FRA) w celu wykrycia PD poprzez identyfikację parametrów uzwojenia za pomocą optymalizacji rojem cząstek (PSO) i określenie jego impedancji w zależności od częstotliwości. Porównanie odpowiedzi częstotliwościowych uzwojenia zdrowego i uszkodzonego pozwala na wykrycie uszkodzenia związanego z wyładowaniem częściowym. (Wykrywanie wyładowań nierzupełnych w uzwojeniu transformatora przy wykorzystaniu analizy częstotliwościowej***)*

Keywords: transformer winding; partial discharge (PD); Particule swarm optimization (PSO); Frequency response analysis (FRA).
Słowa kluczowe: Uzwojenie transformatora; Wyładowania częściowe ; Optymalizacja rojem cząstek ; Analiza odpowiedzi częstotliwościowej.

Introduction

Today, more than ever, power transformers figure among the strategic elements of a transmission and a distribution infrastructure of electricity. Their failure induces important costs during a loss of power or during unexpected maintenance operations. It appears therefore evident, in the frame of their preventive maintenance, of realizing tests and diagnostics that allow following and identifying precociously breakdown symptoms that can appear in the phase of network operation [1].

The majority of the high voltage transformers are made by distinctive kind of strong insulation(i.e., paper, mica, ceramic separators, and spacer etc.) to resist such high voltage stress In this manner, insulation condition checking of such transformers are the most extreme vital schedule work for every power engineers to extend quality and reliability [2].

Degradation of insulation can lead to dangerous situations, serious damage, not to mention significant economic costs. This is why it is important that the insulation state is checked during the long life cycle of a transformer.

Partial discharges (PD) are one of the most frequent causes of weakening insulating material in power transformer windings [3]. The distinguishing proof of PD in high voltage transformers is an essential tool for transformer diagnostics [4]. A partial discharge (DP) is an electrical discharge that only partially bypasses the insulation between two conductors of a winding at different potentials. It can occur in a gaseous cavity inside a solid insulator, at the interface between an insulator and a conductor, or at the surface of an insulator from a triple point (insulator / gas / conductor) [5-20].

A set of calculations and numerous acoustic sensors has been proposed to find PD sources in transformers [6-7]. In any case, when a PD source is found profound interior the winding, the acoustic strategy comes up short to find it [8]. Acoustic signals confront numerous reflections and diffractions, and high damping amid their travel interior the winding.

Currently, frequency response analysis (FRA) has become a relevant tool for transformer diagnostics. However, questions surrounding the interpretation of the frequency response difficulty in mistakes identification and localization. According to the authors, to achieve this, there must be a mathematical system and appropriate formulations [9].

It is obvious that when a fault appears in the winding, its frequency response changes automatically. The FRA technique allows us to have an overview on the state of the winding. However, the analysis and interpretation of the FRA results is considered a challenge.

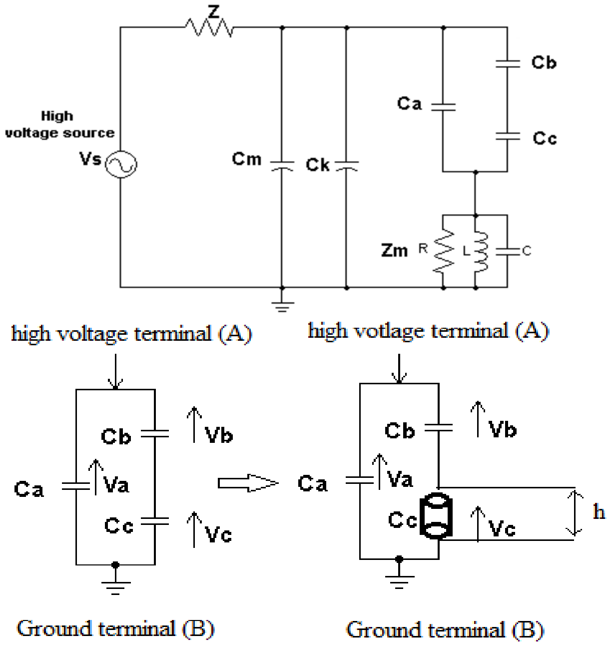

Fig.1. Equivalent circuit and cylindrical void model inside solid dielectric.

Partial discharge model

As known, releases in gas filled cavities implanted in strong dielectrics can be considered as the foremost destructive ones since they are the reason for an irreversible weakening of the HV insulation. In this way, the existing PD models are alluded commonly to releases in gaseous cavities [16].

The classical model (or abc demonstrate or the Gemantvon Philippoff show) is given schematically in Fig (1). An encased depression in strong separator can be spoken to by a capacitance Cc, the insulation following to the depth by a capacitance C_b and the rest of the capacitance of the insulation as C_a [17].

The schematic graph for location of partial release interior the insulation is appeared in Fig (1). It is comprises of channel unit (Z), high voltage measuring capacitor (C_m), coupling capacitor (C_k), void show of strong cover called test question (C_t), and locator circuit for estimation of parcial discharge (Z_m) [18-19].

Transformer winding model

The model of transformer winding is frequently shown with an electrical circuit comprising of a set of resistances (R), inductances (L) and capacitances (C). The winding models can be broadly isolated into two bunches: models based on lumped parameters and models based on conveyed parameters. The foremost overwhelming assignment in both approaches is in deciding the said RLC parameters [1].

The winding of a transformer was modeled at High Frequencies (HF) regimes, under several known models in the literature such as RESEL model, EMTP universal model, Morched model, Chimklai model Gustavsen model, model based on clean and mutual inductances ... etc [11-12]. The model used in this work is the cited model based on self and mutual inductances.

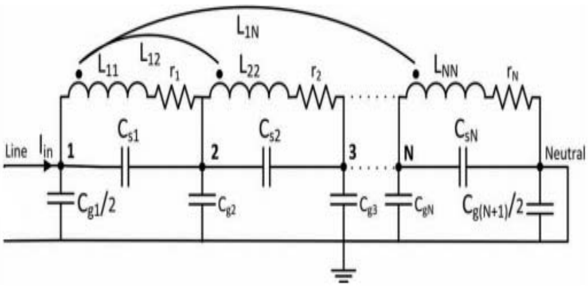

Fig.2. Equivalent circuit of transformer winding.

To decide the parameters of a detailed, estimation strategies can be viable approaches. In a parameter estimation strategy, one highlight of the transformer terminal is measured and endeavors are made to decide the other parameters such that the blunder function; n between simulation and estimation results are minimized.

When considering the fully mutually coupled N-section ladder network that is shown in Fig (2), where every section highlights a disk of the winding. Csi and Cgi are the series and ground capacitances of the i^{th} disk. Lii is the self-inductance of the i^{th} disk and Lij (or Mij) is the mutual inductance between i^{th} -j^{th} disk. These elements are calculated, according to the geometric and dielectric characteristics of the winding, as well as geometric and magnetic characteristics of the magnetic core. They can also be determined experimentally [12], [13].

The cells number N of sections is immenslt difficult, in this research the number N of cells of the model winding is considered equal to the number of resonance frequencies of the impedance winding [13].

The inductance matrix could be formed as following:

$$L = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1N} \\ L_{12} & L_{22} & \cdots & L_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ L_{1N} & L_{2N} & \cdots & L_{NN} \end{bmatrix} \tag{1}$$

The capacitance matrix can be formed as following:

$$C = \begin{bmatrix} C_{S1} + \frac{C_{g1}}{2} & -C_{S2} & \cdots & 0 \\ -C_{S2} & C_{S1} + C_{S2} + C_{g2} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & -C_{(N-1)} & \cdots & C_{S(N-1)} + C_{SN} + C_{gN} \end{bmatrix} \tag{2}$$

The diagonal resistance matrix is given as following:

$$R = \begin{bmatrix} r_1 & 0 & . & . & . & 0 \\ 0 & r_2 & . & . & . & 0 \\ 0 & 0 & . & . & . & r_N \end{bmatrix} \tag{3}$$

Where:

$$r_1 = r_2 = ... = r_N = r \tag{4}$$

$$L_{11} = L_{22} = ... = L_{NN} = L_s \tag{5}$$

$$C_{S1} = C_{S2} = ... = C_{SN} = C_S \tag{6}$$

and

$$C_{g1} = C_{g2} = ...C_{gN} = C_g \tag{7}$$

The self and mutual inductances are represented by the following constraint:

$$0.4L_S < K_1 < 0.9L_S \tag{8}$$

$$0.11M_{i-1} < M_i < 0.99M_{i-1} \tag{9}$$
$$i = 2........,N-1$$

The elements of the capacitance matrix C are selected as following:

- C_{gi} Efficient for the following equation:

$$C_{gi} = \frac{C_{g,eff}}{N} \tag{10}$$

- Voltage distribution constant ‘α’ is repetitively varied according to the experimental impedance [13].
- When N and α are highlighted , the shunt capacitance could be formulated using this equation:

$$C_S = N\,C_{g,eff} \big/ \alpha^2 \tag{11}$$

Particle Swarm Optimization (PSO)

The PSO or the Particle swarm optimizer is an algorithm modeled on swarm intelligence, which finds a arrangement to an optimization issue in a look space, or demonstrates and anticipates social behavior within the presence of objectives. It could be a valuable method to illuminate numerous optimization issues. PSO offers numerous likenesses with developmental computation strategies such as Hereditary Calculations (GA). The framework is initialized with a populace of irregular arrangements and looks for optimized d by overhauling eras [13-15]. This strategy requires less parameters for direction than other optimization calculations and has quicker joining rate for complex optimization problems. The choice of the parameters plays a significant part within the meeting of the PSO calculation unique commitments have proposed to create the standard adaptation of PSO strategy [16-21]. In this study PSO strategy is utilized to assess the parameters of high frequency and localization of faults in a transformer winding, the flowchart of the proposed strategy is initiated in Fig.3.

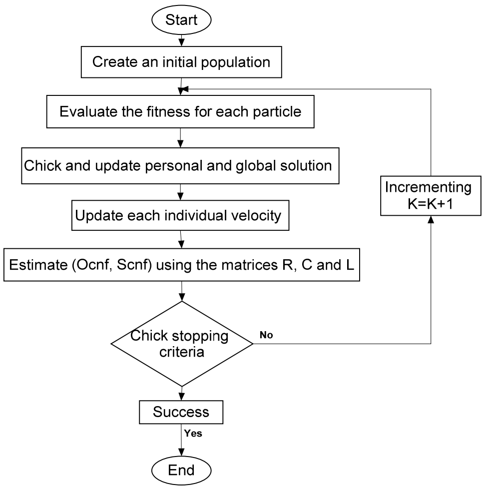

Fig.3. Flowchart of the PSO procedure.

The arbitrary creation of the initial swarm: every molecule consists of the values of the capacitance to the ground and shunt capacitance, the self and common inductances per segment. Every particular set on the starting position concurring to the esteem of the fitness function.

$$L_{eq(estimated)} = NL_1 + 2\sum_{i=1}^{N-1}(N-1)M_{ii+1} \tag{12}$$

The equation (12) presents the fitness function. Compare particle's fitness evaluation with particle's Pbest which is the most suitable position of every particle so far:

$$F(P_i) \geq Pbest_i \rightarrow \begin{cases} Pbest_i = F(P_i) \\ XPbest_i = X_i(k) \end{cases} \tag{13}$$

Compare fitness evaluation with the population's general past gbest:

$$F(P_i) \geq gbest_i \rightarrow \begin{cases} gbest_i = F(P_i) \\ Xgbest_i = X_i(k) \end{cases} \tag{14}$$

Where: gbest is the most suitable position of all generations.

The velocity and position of the particles are updating according to equation (15) and (16) down below:

$$\begin{aligned} V_i(k+1) = {} & WV_i(k) + C_1 rand(Pbest_i(k) \\ & - X_i(k)) + (gbest(k)\_X_i(k)) \end{aligned} \tag{15}$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \tag{16}$$

Where:

$X_i(k)$: The position position of individual i at iteration k

$V_i(k)$: The position velocity of individual i at iteration

$V_i(k+1)$: The adjusted velocity of individual i at iteration $k+1$

$Pbest_i(k)$: The Pbest of individual i until iteration k

$gbest(k)$: The global best of the group until iteration k

C_1, C_2: The acceleration constants

rand: Random number between [0, 1].

When the parameters of the model winding viz (N , L_S , $M_{12} \ldots M_{1N}$, C_g , C_S , r and α) are determined, the matrix of capacitance, resistance and inductance can be formulated. The open and the short circuit of natural frequencies (Ocnf, Scnf) can be considered using the matrices C, R and L.

-The algorithm stops when the following convergence criteria are satisfied:

$$(L_{eq}(estimated) \leq L_{es}(mesured)$$

and

$$(Ocnf\,, Scnf\,)estimated \leq (Ocnf\,, Scnf\,)mesured$$

Within 2% tolerance, otherwise go to step 2.

Identification of the studied winding settings

To check the legitimacy of The proposed approach model, the winding transformer was tested in a research facility starting with the FRA estimations.

The algorithm interpreted by Fig.3. is tested for the identification of the studied winding settings.

After execution of PSO algorithm, the settings of the circuit equivalent of the winding are estimated. The following table recaps the final results.

TABLE .1 SELF AND MUTUAL INDUCTANCES ESTIMED BY PSO.

L_s (mH)	M_1 (mH)	M_2 (mH)	M_3 (mH)	M_4 (mH)
0.18213	0.61286	0.022	0.00794	0.00193

The diversity of the impedance as a function of the frequency of the reference scheme acquired by the diagram estimated by the PSO method is shown in Fig.4.

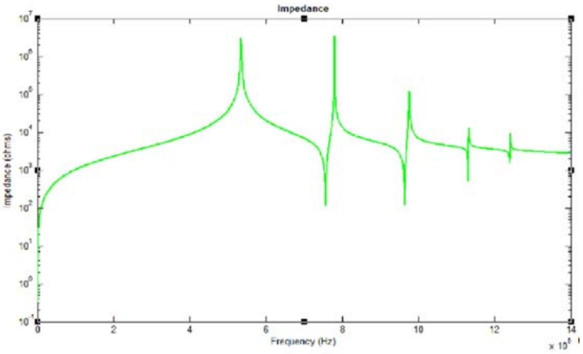

Fig.4. Frequency response obtained by PSO.

Table. 2 (shows the frequencies measured and estimated, as well as the difference recorded between these two quantities. From these results, we confirm the efficacy of the PSO algorithm in this study case.

Table 2. measuring and estimation values comparison using PSO method.

Measured values		**Estimated values by using PSO method**		**Error %**
Ocnf (kHz)	**Scnf (kHz)**	**Ocnf (kHz)**	**Scnf (kHz)**	
536	756	534	757	≤ 1%
779	958	780	963	
970	1127	976	1130	
1129	1246	1132	1239	
1247	-	1241	-	
Leq= 1.55 mH		**L_{eq} = 1.5686 mH**		1.2%

The PSO findings are almost the same, the difference is minimal (<2%). As shown in table (II) , the values are illustrated by numbers where the accurate identification is given. Therefore, the convergence of the PSO is confirmed respecting the investigated problem. The measured and estimated driving-point impedance function of the model winding's plot is shown in Fig.5.

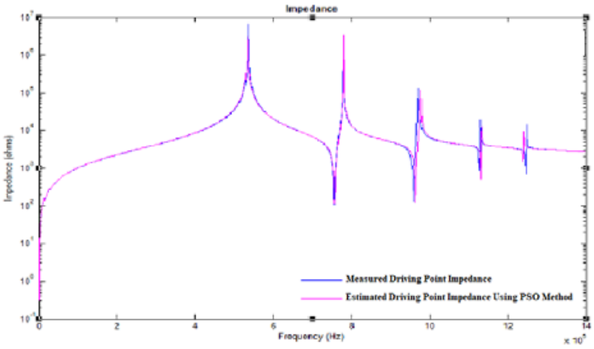

Fig (5): Comparison between estimated and measured driving point impedance.

Any physical change in the winding or part of the winding induces a change in its frequency response. The detection of any deviation or shift to the left or to the right of the cutoff frequencies compared to the signature of a sound winding implies an appearance of a defect in the winding.

After having validated the adopted model, we would exploit it for the transformer winding diagnostic study and that in order to study the defect caused by the partial discharges with the technique of frequency analysis.

Partial discharge defect in the winding

The presence of such a defect in the winding of the power transformer causes a variation of its frequency response, and consequently a variation in the elements of the equivalent circuit. The simulation circuit in Matlab Simumink is given by Fig (6). In this example we have injected the partial discharge into the first cell.

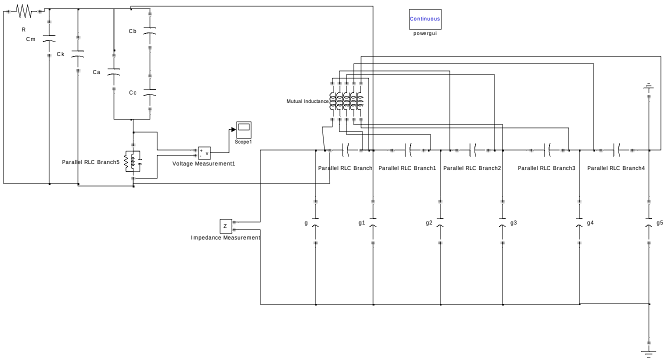

Fig (6): Equivalent diagram of transformer winding with partial discharge.

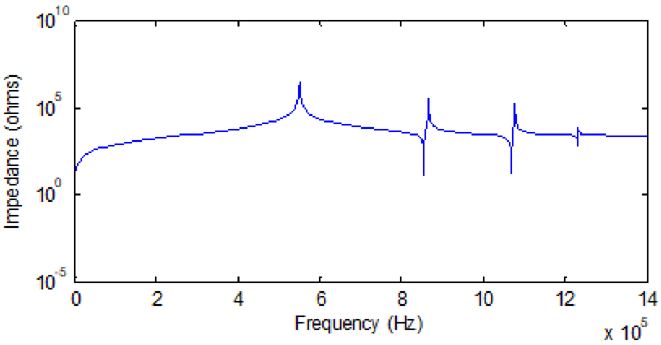

Fig.7. Variation of the impedance as a function of the frequency of a winding with a DP in the first cell

The impedance's variation as a function of the frequency of the reference shot with partial discharge injected into the first disk is illustrated in Fig (7).

Table 2. shows the frequencies of the healthy and the partially discharged windings, as well as the difference recorded between these two magnitudes.

Table 3. Comparing the frequency response between a healthy winding and a winding having a PD defect in the first cell.

Healthy winding		Winding with PD		Difference	
Ocnf (KHz)	Scnf (KHz)	Ocnf (KHz)	Scnf (KHz)	Ocnf (KHz)	Scnf (KHz)
534	757	550	856	16	99
780	963	869	1071	89	108
976	1130	1082	1226	106	96
1132	1239	1227	-	95	-
1241	-	-	-	-	-

From the comparison between the impedance imprint of a healthy wound and other from a winding having a partial discharge fault in the first cell, we observed a displacement of the frequencies (Ocnf) and (Scnf) of about 16KHz-100KHz respectively.

We also notice, after the default application, the disappearance of the cut frequencies at the last disc observed in the case of a healthy winding.

We applied the same DP for each cell one by one, and the results obtained are given in the Fig.8.

Fig.8. represents a comparison between the responses of all the partial discharge faults and the response of the winding in the healthy state. We observed a displacement of the partial discharge point in the winding, which explains the shift to the right of the cut-off frequencies of the frequency responses of the winding in fault and that in comparison to the response of the winding.

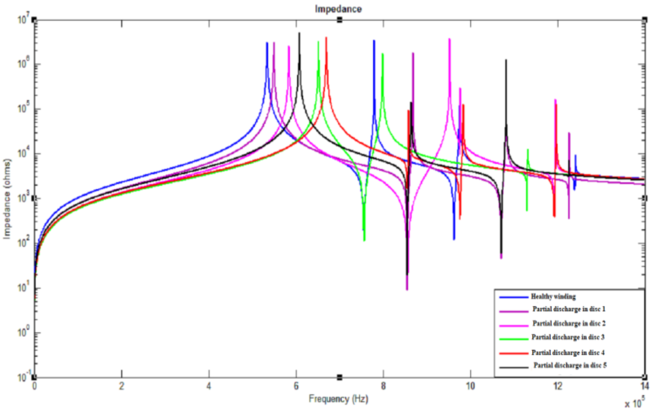

Fig.8. Comparison between the frequency responses of healthy winding and the winding affected by the DP in each cell.

Conclusion

As a conclusion this paper represents a study case of the FRA method for the detection of partial discharge in a winding of a power transformer.

At First the electrical model equivalent of a partial discharge, has been presented then a model of a transformer winding and estimated its parameters using the PSO algorithm has been presented. As a follow, the frequency's response to the impedance of the healthy winding and the winding in failure of a partial discharge has been presented and at last a comparison between its responses has been made.

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