Transformer winding faults diagnosis using the transfer function of its high-frequency lumped equivalent model from the measured FRA data

Diagnóstico de falhas de enrolamento do transformador usando a função de transferência de seu modelo equivalente agregado de alta frequência dos dados FRA medidos

Diagnóstico de fallas de bobinado de transformador utilizando la función de transferencia de su modelo céntrico de alta frecuencia a partir de datos medidos FRA

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ABSTRACT
The frequency response analysis (FRA) of the transformer is the data obtained in a wide frequency range that represents the transfer function (TF) that reflects the physical behavior of its coil. However, it can be considered one of the best tools for a better understanding of the electromagnetic characteristics of the winding. This article proposes the TF as a tool to locate and assess transformer winding failures. So, an autonomous algorithm has been developed to construct the TF in ‘s domain’ proposed in previous research. The TF has been determined from experimental measured FRA data from an isolated air-core winding, where the TF has been calculated for the axial defects (AD) realized on the winding discs. Besides, the diagnostic approach is based on the scaling factor (K) and the real zero (τ) of the TF that can be obtained from the measured equivalent capacitance, equivalent inductance, and the DC resistance of the winding in high and low-frequency ranges. However, the K, τ, and the slope of the equivalent inductance characteristics as a function of the winding defects degree have been used for locating and assessing the severity of the winding faults.

Keywords: axial defects, frequency response analysis, transformer winding, transfer function.

RESUMO
A análise de resposta de frequência (FRA) do transformador são os dados obtidos em uma ampla faixa de frequência que representa a função de transferência (TF) que reflete o comportamento físico de sua bobina. No entanto, pode ser considerada uma das melhores ferramentas para uma melhor compreensão das características eletromagnéticas do enrolamento. Este artigo propõe o TF como uma ferramenta para localizar e avaliar falhas de enrolamento do transformador. Assim, um algoritmo autônomo foi desenvolvido para construir o TF no "domínio de" proposto em pesquisas anteriores. O FT foi determinado a partir de dados FRA experimentais medidos a partir de um enrolamento isolado do núcleo de ar, em que o FT foi calculado para os defeitos axiais (AD) realizados nos discos de enrolamento. Além disso, a abordagem diagnóstica é baseada no fator de escalonamento (K) e no zero real (τ) do TF que pode ser obtido a partir da capacitância equivalente medida, inductância equivalente, e a resistência CC do enrolamento em faixas de alta e baixa frequência. No entanto, o K, τ, e a inclinação das características de inductância equivalentes em função do grau de defeitos de enrolamento têm sido usados para localizar e avaliar a gravidade das falhas de enrolamento.

Palavras-chave: defeitos axiais, análise de resposta de frequência, enrolamento do transformador, função de transferência.

RESUMEN
El análisis de respuesta de frecuencia del transformador (FRA) es la información obtenida sobre un amplio rango de frecuencia que representa la función de transferencia (TF) que refleja el comportamiento físico de su bobina. Sin embargo, puede considerarse una de las mejores herramientas para un mejor entendimiento de las características electromagnéticas del bobinado. Este artículo propone el TF como herramienta para la localización y evaluación de fallas en el devanado de transformadores. Así, se desarrolló un algoritmo autónomo para construir el TF en el "dominio de" propuesto en investigaciones previas. La FT se determinó a partir de datos experimentales de FRA medidos a partir de un bobinado aislado de núcleo de aire, donde se calculó la FT para los defectos axiales (AD) realizados en los discos de bobinado. Además, el enfoque diagnóstico se basa en el factor de escala TF (K) y el cero real (τ) que se pueden obtener a partir de la capacitancia equivalente medida, la inductancia equivalente y la resistencia CC del bobinado en rangos de alta y baja frecuencia. Sin embargo, K, τ y la pendiente de las características de inductancia
equivalentes en función del grado de defectos del bobinado se han utilizado para localizar y evaluar la gravedad de los fallos del bobinado.

**Palabras clave:** defectos axiales, análisis de respuesta de frecuencia, devanado de transformador, función de transferencia.

1 INTRODUCTION

Electrical energy (AC and DC generators, and solar energy [1], [2]) are the key elements in the electrical network. However, the transmission and distribution of electrical energy is done via the transformer which is one of the main elements in the network. Frequency response analysis (FRA) is one of the best ways adopted in the power transformer fault diagnosis field [3-6]. The FR response of the winding reflects its electrical and magnetic characteristics in a wide frequency range [7]. Recently, researchers have paid great attention to the transformer winding deformations diagnosis to locate and assess its severity. However, the lumped mutually coupled equivalent model of transformer winding is one of the best ways to interpret and understand its physical behavior [7]-[9]. The mutually coupled equivalent model reflects the physical characteristics of transformer winding. However, the driving point impedance (DPI) function of transformer winding contains all the parameters (inductances and capacitances) of this equivalent model physically realizable, in which each parameter exists in its frequency range. These parameters can, therefore, be used as diagnosis tools based on the DPI curve in its frequency ranges [10]. Besides, the statistical numerical indices have also been used for transformer fault diagnosis based on classification approaches (e.g. SVM method [11]). Ideally, understanding the transformer winding behaviors in the frequency domain may effectively contribute to their fault’s interpretation. However, the physical properties of the winding can be represented by electrical parameters that reflect the behavior of these properties in a specific frequency range. The lumped equivalent model is the best way to analyze and interpret the frequency response of transformer windings. The lumped circuit has a good ability to simulate the physical properties of the winding, where its parameters most accurately reflect the frequency characteristics of the winding. As a result, the mutually coupled equivalent circuit construction is a challenging task that is generally based on the detailed geometrical construction of the winding which is usually not possible. Besides, the synthesis of this model is also based on optimization methods such as; Mukherjee 2011 [12], Chaouche 2018 [13], and Ren 2019 [14]…etc. were used the Ant Bee Colony (ABC), Bat Algorithm (BA), and Gauss New Iteration Algorithm (GNIA) methods respectively which depend on the
determining of the search space of the parameters to be estimated, where these algorithms reach approximative solutions, where, the extraction of these parameters from the FR of the winding using direct or indirect measurement approaches is an effective effort [15]-[17]. In addition, the transfer function of the lumped equivalent model can be an effective tool for understanding and interpreting the physical behavior of the winding to determine its parameters [18]. This initiative was a new entry in the model synthesis field to diagnose its faults. The authors in [19] have proposed the transfer function method to estimate the parameters of this model. The diagnostic task is the goal of all research in this field. However, Shah and Ragavan [15] have synthesized the circuit model in a healthy and defective state to locate and assess the mechanical deformations of the transformer winding. Ren et.al [14] have used the GNIA method to diagnose winding damages by optimizing its equivalent circuit model parameters. In these efforts, the construction of the reference circuit model is explored by researchers to localize actual mechanical damages in actual windings using the FRA measurement. Besides, the non-homogeneous circuit model (corresponding to the faulty case) construction using optimization algorithms implies an increased number of parameters to be optimized with significant computation time. However, understanding the FRA signal morphology allows a suitable interpretation of the physical properties of the system being studied (e.g. transformer) which can indicate the mechanical deformation behavior of the winding. In this article, the transfer function expression developed by [18] has been determined for a multi-resonant frequency response of an actual isolated winding to use its parameters (the K, τ factors, and the slope of the equivalent inductance) in locating and assessing the winding defects. However, these parameters corresponding to the electromagnetic effects of the winding can be determined from the FR curve in the low and high frequencies.

2 HIGH FREQUENCY MUTUALLY COUPLED EQUIVALENT CIRCUIT OF TRANSFORMER WINDING

The high frequency mutually coupled equivalent model of transformer winding as in Fig.1 is comprised of N section network magnetically coupled by mutual inductances (M_ij) between ith – jth section, in which each section comprised by DC resistance (r) and self-inductance (L_ii), the ith section is electrically coupled between turns by series capacitances (C_si), and, between turns and ground by shunt capacitances (C_gi). The reference circuit of a healthy winding is homogeneous, and thus the parameters (resistances, self-inductances and series and shunt capacitances) of all sections are equals. The magnetic
coupling is therefore symmetrically distributed between the model sections, and thus $M_{12} = M_{23} = ..., M_{12} = M_{24} = ..., etc.$

Figure 1. High frequency mutually coupled equivalent circuit of transformer winding

Source: The authors, 2021

3 PARAMETERS EXTRACTION PROCEDURE OF THE WINDING FROM ITSMeasured DPI

The main parameters of transformer winding such as; the DC resistance, the equivalent inductance, the equivalent capacitance, and the open and short natural frequencies can be extracted directly from the FR data curve of the impedance in the frequency domain. However, the figure shows the extracting procedure of these parameters each of them in its frequency region LFR, MFR, or HFR. These parameters are essential to construct the lumped mutually coupled model. The transfer function contains all the main parameters of the winding. Furthermore, this function is a function of the $K$ factor and, the pair conjugates complex poles $p_i, p_i^*$ and zeros $z_i, z_i^*$ in ‘s domain’ as in equation (1) [18], [20].

$$Z(s) = (K(s - T)) \prod_{i=1}^{(N-1)} \left( \frac{s - Z^*(s - Z^*))}{(s - P^*(s - P^*))} \right)$$

Where:

$$z_i = -\delta_i \mp j\varphi_i \forall i = 1, ..., N-1.$$  

$$p_i = \sigma_i \mp j\omega_i \forall i = 1, ..., N.$$
\[ \sigma_i = \omega_{(0,i)}/2Q \] and \[ \omega_i = \sqrt{\omega_{(0,i)}^2 - \sigma_i^2} \] \hspace{1cm} (2)

With, \( Q \) is the quality factor at the resonant pulsation \( \omega_{(0,i)} \).

If \( Q \gg 1 \), \[ \sigma_i = \frac{\omega_{(h,i)}-\omega_{(l,i)}}{2} \] \hspace{1cm} (3)

Where:

\( \omega_{h,i} \) and \( \omega_{l,i} \) represent the lower and higher frequencies at \( Z_{\max}/\sqrt{2} \) in \( \omega_{0,i} \), respectively.

Figure 2. Extracting procedure of the main parameters of the lumped mutually coupled network of the transformer winding.

\[ \delta_i = \frac{\phi_{h,i}-\phi_{l,i}}{2} \] and \[ \phi_i = \sqrt{\phi_{0,i}^2 - \delta_i^2} \] \hspace{1cm} (4)

Where:

\( \phi_{h,i} \) and \( \phi_{l,i} \) represent the lower and higher frequencies at \( \sqrt{2} \) \( Z_{\min} \) in \( \phi_{0,i} \), respectively.
3.1 EXTRACTING THE EQUIVALENT INDUCTANCE AND DC RESISTANCE FROM THE DPI

The DPI curve obtained from the FRA test with neutral shorted of the winding with air core in the low-frequency range (0 Hz-1000 Hz) is a straight line increasing with frequency. In which, the DC resistance can be extracted at very low frequencies (very close to 0 Hz). The linear part of the FR curve represents the inductive effect of the winding, where the equivalent inductance ($L_{eq}$) can be extracted directly from the FR curve in this frequency range as shown in Fig. 2. The equivalent inductance of the winding is therefore representing the slope of the linear part of the FR curves, in which this slope changes according to the $L_{eq}$ value that is affected by the winding damages.

$$\lim_{s \to 0} Z(s) = R_{dc} + sL_{eq} \quad (5)$$

Where:

the $\tau$ value can be obtained as follow $\tau = \frac{-R_{dc}}{L_{eq}}$.

3.2 EXTRACTING THE EQUIVALENT CAPACITANCE IN THE HFR RANGE

As shown in Fig.2, at high frequency, after the last $O_{cnf}$ the lumped mutually coupled circuit becomes a circuit with capacitances only because in this region the magnetic effect is negligible. However, the lumped model can be modeled by the shunt and the series capacitance, where the total equivalent capacitance ($C_{eq}$) can be extracted from the measured DPI function. In this frequency range the transfer function is a hyperbolic function containing the capacitance effect only as shown in equation (6), its value must remain constant over a specific frequency range where the phase angle of the impedance is approximately equal to 90°, such that the resistive effect is also negligible [15].

$$z(s)_{HFR} = \lim_{s \to \infty} z(s) = \frac{\sin \theta}{sC_{eq}} \quad (6)$$
3.3 EXTRACTING THE OPEN AND SHORT NATURAL FREQUENCIES IN THE MFR RANGE

In the mid-frequency range, the transfer function is affected by the interaction between inductive and capacitive effects which cause the open and short natural frequencies \((O_{cnfs}, S_{cnfs})\) which represent the poles and zeros of the TF in ‘s domain’. Here, at \(s = 0\), the scaling factor \(K\) can be determined from equation (1) its value turns around \(1/C_{eq}\) as a function of \(L_{eq}, O_{cnfs}\) and \(S_{cnfs}\) as in equation (7) [18], [20].

\[
K = z(s)_{HFR} = L_{eq} \frac{\prod_{i=1}^{N-1} S_{cnfs}^2}{\prod_{i=1}^{N} O_{cnfs}^2} (7)
\]

The \(K\) factor can be considered as a useful tool for analyzing and interpreting transformer winding failures. Besides, this factor varied according to the equivalent inductance and the resonance and antiresonance points of the winding response, which are measurable quantities, so the K factor was proposed in this paper to locate and evaluate the severity of the winding discs’ faults.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 DETERMINING THE TRANSFER FUNCTION OF THE LUMPED MODEL

The DPI function curve depicted in figure.1 has been measured from the winding terminals in a wide frequency range (20 Hz-2MHz) [9], where \(L_{eq} = 9.72 \text{ mH, and } R_{dc} = 2.4 \Omega\), the value of \(\tau = -0.00024691 \text{ M. neper/}\text{s} and K = 3.7789 \times 10^{10}\). However, its curve is composed of five (05) and four (04) open and short circuit natural frequencies which represent the poles and zeros of the transfer function respectively. The values of these pair complexes conjugate poles and zeros have been calculated using the procedure proposed in [20] and are illustrated in table.1.
Table 1. Pair complexes conjugate poles and zeros in (M. rad/s)

<table>
<thead>
<tr>
<th>$z_i$</th>
<th>$\phi_{0,i}$</th>
<th>$\omega_{0,i}$</th>
<th>$\rho_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.590067</td>
<td>0.07857 + 2.588874i</td>
<td>1.389390</td>
<td>0.05657 + 1.388237i</td>
</tr>
<tr>
<td>4.268500</td>
<td>0.1351 + 4.266359i</td>
<td>3.067823</td>
<td>0.0880 + 3.066560i</td>
</tr>
<tr>
<td>5.607474</td>
<td>0.23259 + 5.602648i</td>
<td>4.664534</td>
<td>0.1414 + 4.662389i</td>
</tr>
<tr>
<td>6.852155</td>
<td>0.3771 + 6.84176650i</td>
<td>5.896642</td>
<td>0.2703 + 5.890443i</td>
</tr>
<tr>
<td></td>
<td>7.153895</td>
<td></td>
<td>0.4871 + 7.137287i</td>
</tr>
</tbody>
</table>

Source: The authors, 2024

The transfer function expressions were obtained with a numerator and denominator for the winding in the health and defective conditions as shown in Table 2.

4.2 FRA FAULTS INTERPRETATION

The defects effect (viz. RD, AD, and SC) on the DPI function of the winding is slight in the low-frequency range, which is evident from the curves represented in Figure 6 due to the dominant influence of the inductance in this frequency range. However, this effect becomes more apparent and more interesting with increasing frequency in the medium frequency range due to the multiple effects of inductance and capacitance that form the open and short natural frequencies, as it appears more clearly at the last resonance points, while...
this effect returns to fading in the high-frequency range, as is evident after the last resonance due to the capacitive effect only due to the disappearance of the inductive effect at this range. Figure 6 shows a comparison of the FRA data in the event of an axial failure between rings 2 and 3 with increasing damage with the FRA data in its healthy state, where the effect of the model parameters on the various frequency bands is evident, as stated previously.

Figure 6. FR curves for different AD faults degrees

![Figure 6](image-url)

Source: The authors, 2024

In this article, the $K$ and $\tau$ factors were highlighted as a tool for analysing and interpreting the FR curves of the winding faults. The $K$ changes in terms of the equivalent inductance of the winding and the open and short natural frequencies extracted from the FR curves, which makes it contain all the parametric effects of the faults. Whereas, the $\tau$ factor changes in terms of the equivalent inductance and the DC resistance of the winding. The $K$ and $\tau$ factors have been calculated for different fault degrees to use as a tool in interpreting and evaluating the defect's severity in the windings (Table.3), as it is clear from Figure 7 and 8, which represent the $K$ and $\tau$ factors in terms of equivalent inductance. In the AD displacement the $R_{dc}$ does not change with fault degree, so the $\tau$ factor is a linear function.
with a constant slope $1/R_{dc}$.

Furthermore, in the low frequencies range the impedance is a linear function of equivalent inductance slope where this later shifts with $\alpha(°) = \arctan(L_{eq})$ as a function of the AD faults which is illustrated in table 3. This parameter is plotted in terms of the AD fault degrees as depicted in Figure 9.

<table>
<thead>
<tr>
<th>Health case</th>
<th>The transfer function $z(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD fault of 5 mm</td>
<td>$\frac{3.779e10 \ s^9 + 6.233e16 \ s^8 + 3.948e24 \ s^7 + \cdots + 4.781e56 \ s^2 + 6.866e63 \ s + 1.666e67}{s^{10} + 2.087e06 \ s^9 + 1.206e14 \ s^8 + 1.724e20 \ s^7 \cdots + 5.114e53 \ s^2 + 8.824e58 \ s + 7.072e65}$</td>
</tr>
<tr>
<td>AD fault of 8 mm</td>
<td>$\frac{3.737e10 \ s^9 + 5.403e16 \ s^8 + 3.779e24 \ s^7 + \cdots + 3.918e56 \ s^2 + 6.123e63 \ s + 1.567e66}{s^{10} + 1.094e06 \ s^9 + 1.156e14 \ s^8 + 9.166e19 \ s^7 + \cdots + 4.7e53 \ s^2 + 6.277e58 \ s + 6.527e65}$</td>
</tr>
<tr>
<td>AD fault of 14 mm</td>
<td>$\frac{3.667e10 \ s^9 + 4.52e16 \ s^8 + 3.647e24 \ s^7 + \cdots + 3.285e56 \ s^2 + 5.601e63 \ s + 1.456e66}{s^{10} + 1.018e06 \ s^9 + 1.136e14 \ s^8 + 8.521e19 \ s^7 + \cdots + 4.433e53 \ s^2 + 5.824e58 \ s + 6.065e65}$</td>
</tr>
<tr>
<td>AD fault of 17 mm</td>
<td>$\frac{3.269e10 \ s^9 + 4.829e16 \ s^8 + 3.217e24 \ s^7 + \cdots + 3.111e56 \ s^2 + 4.671e63 \ s + 1.243e66}{s^{10} + 8.926e05 \ s^9 + 1.116e14 \ s^8 + 7.106e19 \ s^7 + \cdots + 4.223e53 \ s^2 + 4.772e58 \ s + 5.749e65}$</td>
</tr>
<tr>
<td>AD fault of 17 mm</td>
<td>$\frac{3.13e10 \ s^7 + 2.441e16 \ s^6 + 1.994e24 \ s^5 + \cdots + 5.997e42 \ s^2 + 1.3e50 \ s + 3.489e52}{s^8 + 9.618e05 \ s^7 + 7.629e13 \ s^6 + 4.658e19 \ s^5 + \cdots + 1.151e40 \ s^2 + 1.557e45 \ s + 1.618e52}$</td>
</tr>
</tbody>
</table>

Source: The authors, 2024

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Health winding</th>
<th>AD faults degree’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K \ factor \times 10^{10}$</td>
<td>3.77</td>
<td>3.73</td>
</tr>
<tr>
<td>$\tau (M. neper) \ s^{-1}$</td>
<td>$-0.000250$</td>
<td>$-0.0002558$</td>
</tr>
<tr>
<td>$L_{eq} (mH)$</td>
<td>9.702</td>
<td>9.549</td>
</tr>
<tr>
<td>$\alpha (°)$</td>
<td>0.5511</td>
<td>0.54712</td>
</tr>
</tbody>
</table>

Source: The authors, 2024
Figure 7. The K factor in term of $L_{eq}(mH)$ for different AD degrees between discs 2 and 3

Figure 8. The $\tau \left( M_{\text{neper,s}} \right)$ factor in term of $L_{eq}(mH)$ for different AD degrees between discs 2 and 3
Figure 9. The slope $\alpha(\degree)$ in term of $L_{eq}(mH)$ for different AD degrees between discs 2 and 3

5 CONCLUSION

In this work, the transfer function of the lumped mutually coupled isolated air core winding has been calculated based on previous procedure research to use it as a tool for their fault’s interpretation. However, the K and $\tau$ factors of the transfer function in terms of the equivalent inductance have been highlighted as diagnosis tools of the winding. Furthermore, the slope of the equivalent has also been proposed as a locating and assessing tool for the severity of these defects. The diagnosis way can be considered an effective tool for the winding fault assessment as it is based only on the measurement of the winding parameters. Experimental AD defects have been realized between the actual winding based on its measured data in the frequency domain.
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