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CHARACTERIZATION OF CORE EFFECT ON FREQUENCY RESPONSE ANALYSIS IN POWER TRANSFORMERS

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Abstract- The magnetic core has major effects on power transformers frequency response analysis (FRA) results at low frequencies. To obtain criteria for interpreting of power transformers FRA results, it is necessary to accurately consider the effects of the frequency-dependent characteristics of the core i.e. permeability and eddy current losses, core saturation, material type of the core magnetic steel, core structure (3-limb core or 5-limb core) and core magnetization on the frequency response traces. In this paper, a 3-phase detailed model is used to characterize the core effect on power transformers FRA results. The results proved that the core saturation and material of the core magnetic steel has an observable effect in the frequency range up to 10 kHz and the effect of core construction is considerable at frequencies up to 100 kHz.

Keyword: Power Transformer, Frequency Response Analysis (FRA), Core Characteristics, Core Magnetization, Core Saturation.

I. INTRODUCTION

Power transformers are among the most important component of a power system. During their lifetime they are exposed to various mechanical and electrical faults which are originated from mechanical or electromagnetic forces caused by short-circuit currents and ageing (Dick and Erven 1978 [1], Lapworth and McGrail 1999 [2], McDowell and Lockwood 1994) [3]. Desirable condition assessment, maintenance scheduling and improved operational efficiency of transformers is related to early as possible detection and diagnosis of transformer faults.

One of the well-known methods for on-site and early diagnosis of power transformers is frequency response analysis. The FRA method is based on the fact that each winding has a unique transfer function which changes in its parameters namely resistance, inductance and capacitance will alter the amplitude, phase and resonance points of transfer function [4-5]. Several efforts have been carried out to improve interpretation ability of FRA method. One of the widely used approaches is power transformer modeling.Power transformers are modeled diversely depending on the model application. Rashtchi *et al.* (2011) [6] presented a general classification for transformer modeling. Among different modeling approaches, the detailed model is determined exclusively from the transformer geometrical dimensions and its validity is proven for frequency range up to 1 MHz. This model has been used for a wide variety of proposes by researchers (Buckow 1986 [7], Gharehpetian *et al.* 1998 [8], Rahimpour *et al.* 2000 [9], Rahimpour *et al.* 2003) [10]. In this study the detailed 3-phase model of transformer windingswhich proposed by (Mitchell and Welsh, 2011) [11] is used for investigating the magnetic core effects on FRA results.

There are very limit research efforts on the subject of core effects on power transformers FRA results. The main work has been carried out by Abeywickrama*et al.*(2008) [12] where they have performedFRA tests on two distribution transformers and measured three impedance transfer functions at three different core conditions. The results has shown that the mainly effect of the core magnetization introduces at low frequencies up to ~10 kHz. The magnetic viscosity causes the winding impedance to change with time and this makes comparison of two FRA traces more difficult. In [13] it has been shown that the admittance transfer function is more sensitive to core effects than voltage transfer function and also the core saturation results in displacement of resonance frequencies. The objective of this research work is to present a comprehensive study about the core effect on power transformer's FRA results using a 3-phase detailed winding model of a 1.3 MVA 11-kV/433-V, Dyn1 distribution transformer. The study considers the effect of the core saturation, material of the core magnetic steel, frequency dependent nature of resistance and permeability, and the construction of core i.e. shell or core types on FRA results.

The paper is structured in the following manner. Section II gives a brief description on 3- phase detailed model of power transformers and calculating the complex permeability and frequency- dependent resistance. Section III investigates and characterizes the core material, core magnetizing, core saturation and core structure (shell type and core type) on FRA results. The simulation results and discussions on the results will be presented in section IV. Finally, conclusion will be given in section V.

II. WINDING DETAILED MODEL [11]

The detailed model for a generic phase of a transformer has been illustrated in Figure. 1. It consists of resistive, inductive and capacitive elements. Each of these elements is described in the following. According to [11], the generic high-voltage terminals are designated $X-Y-Z$, and corresponding low voltage terminals are $x-y-z$ [11].

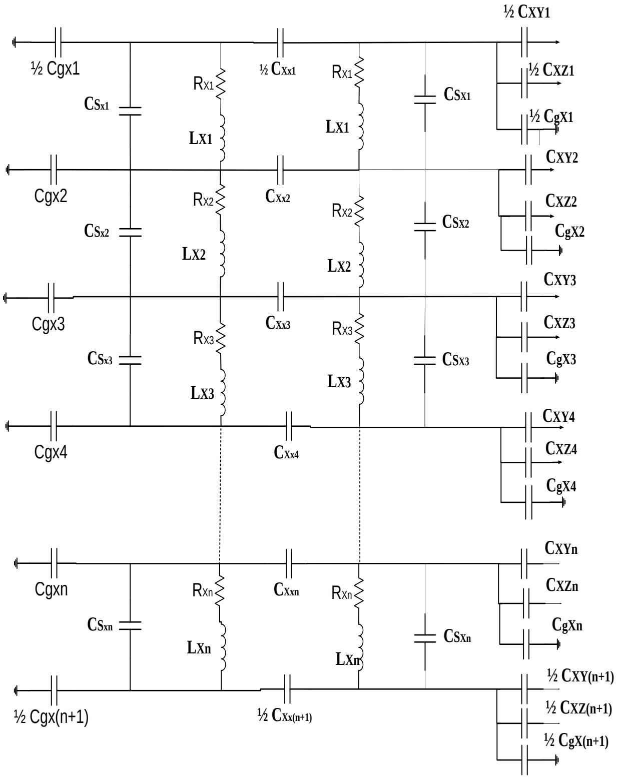


Figure 1. The detailed model of the transformer for a generic phase

A. Resistance

The winding resistance includes a dc and a frequency-dependent AC part. The DC part relates to the conductor resistivity and its cross sectional area and the AC part originates from induced eddy current within the winding that can be considered as skin and proximity effects. The ac resistance due to skin effect is as follows (Mitchell and Welsh, 2011) [11]:

$$R_s = \frac{R_{DC}}{2}\xi\left[\frac{\sinh\xi+\sin\xi}{\cosh\xi-\cos\xi}\right] \tag{1}$$

where

$$\xi = \frac{d\sqrt{\pi}}{2\delta} \tag{2}$$

where d is the conductor diameter, δ is the skin depth and equals to $\delta = \frac{1}{\sqrt{\pi f \mu\sigma}}$, f is the frequency, and μ and σ are the permeability and conductivity of the conductor magnetic steel, respectively. The resistance due to m-th winding layer proximity effect is [11]:

$$R_P = \frac{R_{DC}}{2}\xi\left[(2m-1)^2\frac{\sinh\xi-\sin\xi}{\cosh\xi+\cos\xi}\right] \tag{3}$$

B. Capacitance

The capacitance between turns and adjacent discs is modeled with C_{SX} and C_{Sx} for high and low voltage windings respectively. C_{gX} and C_{gx} are the capacitance between the winding and tank walls for high and low voltage windings respectively. The capacitance between the adjacent high voltage windings are C_{XY}, C_{YZ} and C_{ZX}, and C_{XX} is the capacitance between the high and low voltage windings.

C. Self and Mutual Inductances

The modelutilizes a magnetic circuit based on the transformer's core geometry. Each winding is replaced with a magneto motive source and each flux path contains the leakage and reluctance in the magnetic circuit. The core reluctance can be defined in terms of the mean path length (l), core cross-sectional area (A_{cs}), and the core permeability (μ). The limb resistance is $R_y = \frac{l_E}{\mu A_{cs}}$ and the yoke resistance is $R_y = \frac{l_y}{\mu A_{cs}}$. This circuit model includes the self and mutual inductance in the each phase. The permeability of the transformer core is a complex frequency-dependent term and under low-field conditions and thewide frequency spectrum of an FRA test, it can be defined as [14]:

$$\mu = \frac{k\mu_i\mu_0}{\gamma b}\tanh\gamma b \tag{4}$$

In equation (4), μ_0 is the permeability of the free space, μ_i is the initial permeability of the coremagnetic steel, k is the lamination stacking factor, b is the core lamination half thick, and γ isthe propagation constant which define as follow [14]:

$$\gamma = \sqrt{j\omega\sigma\mu_i\mu_0} \tag{5}$$

Due to the presence of two windings per phase in a real-life transformer, mutual inductive and capacitive couplings between the sections of the same winding as well as that of different windings significantly change the transfer function from transformer to transformer.

As mentioned, the permeability of the core depends on the frequency. Figure 2 shows the real and imaginary part of the permeability of the transformer core. It can be seen that the real and imaginary part of permeability have different values at low frequencies, but at high frequencies their values are identical.

III. MODELING CORE EFFECTS

In this section the factors related to the core including core material, core magnetization, core saturation and core structure are investigated in details.

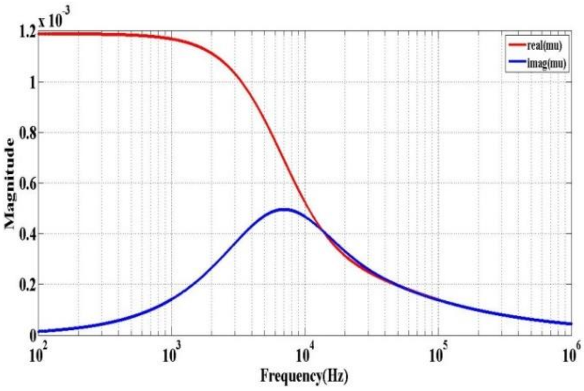


Figure 2. Permeability of transformer core (real and imaginary parts)

A. Core Material (Magnetic Steel) [15-16]

Choosing the right lamination material for a particular application is an important design step, since lamination properties have a different impact on the core losses. Due to the importance of enhanced electrical core performance, researchers are very active in development of better material for the transformer cores. In this study, three conventional magnetic steels namely M-4, M-5 and M-6 are considered to illustrate the impact of the number and thickness of the laminations on the transformer FRA results.Table 1, presents the properties of the mentioned magnetic steels which are used for the simulation of the 1.3 MVA distribution transformer FRA. The real part and the imaginary part of the mentioned core steels are depicted in Figure 3 [15-16].

B. Core Magnetization

When the transformer is disconnected from the network, a state called magnetic relaxation or magnetic after-effect occurs due to thermal activation of the irreversible magnetization processes [12]. The time dependency of this magnetization is generally described as [12] $\mu(t)=\mu(0)-s_{\mu}.\ln(t/t_0)$ where the first and second terms denote the irreversible and reversible components, respectively. To model the magnetization effect, we consider three levels:

Level 1- directly after disconnecting the transformer from the network. In this level the magnetic relaxation hasmore reversible components and therefore, the permeability has a high value.

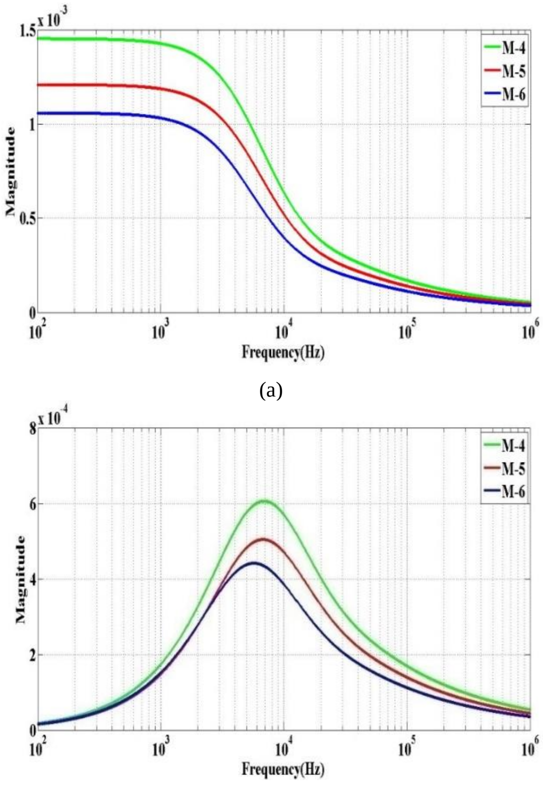
Level 2- a few times after disconnecting the transformer from the network. In this state, some of the reversible components of the magnetic relaxation have been reversed and the permeability is lessthan level 1.

Level 3- sufficient time after disconnecting the transformer from the network. In this level, all of the reversible components of the magnetic relaxation have approximately been reversed.

Figure. 4 shows the real and imaginary part of the permeability for the above mentioned levels. As it is obvious from Figure.4, the magnetization of core will decline as time is elapsed and will cause to reduction of core permeability. This effect is more sensible at low frequencies.

Table 1. Magnetic laminations characteristics

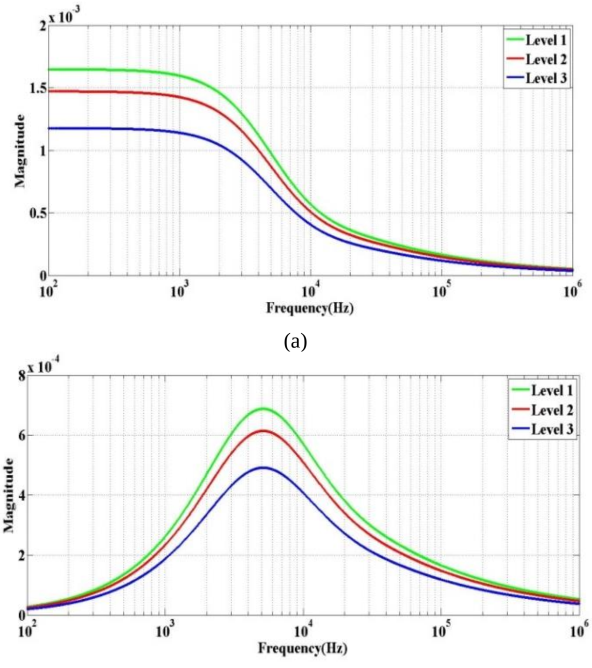
Grade AISI designation (GOES designation)	Thickness in inches (mm)	Stacking factor (%)
M4	0.011 (0.27)	96.00
M5	0.012 (0.30)	96.50
M6	0.014 (0.35)	97.00



(a)

(b)

Figure 3. Permeability of different magnetic steels: (a) Real art of permeability, (b) Imaginary art of permeability



(a)

(b)

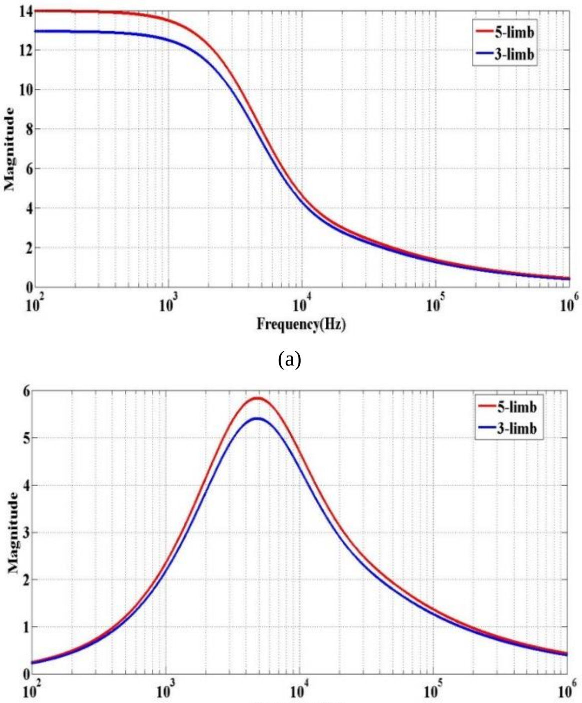
Figure 4. Effect of core magnetization on permeability: (a) Real art of permeability, (b) Imaginary art of permeability

C. Core Saturation

The magnetic circuit determines the quality of the flux distribution inside the transformer. Therefore, it influences the inductances and so the frequency response. As it is obvious the core inductance is directly proportional to core magnetic permeability. The relationship between the magnetizing filed (*H*) and the flux density (*B*) is expressed as the magnetic permeability. Due to core saturation, the magnetic permeability of the transformer core reaches a maximum value and then decline. This causes the magnetizing inductance to decrease and then at low frequencies the transformer winding less attenuates the frequency response amplitude.

D. Core Structure

Transformers with 5-limb core may be used to reduce the overall height of 3-limb core transformers. In the 5-limb cores, there are two additional lateral legs in comparison with the 3-limbcores. These two lateral legs provide additional path for flux and therefore reduce the core reluctance resulting in increased core inductance. The inductances for 3-limb and 5-limb cores are illustrated in Figure 5.



(a)

(b)

Figure 5. Inductances of 3-limb and 5-limb core. A) Real art of permeability, B) Imaginary art of permeability

IV. RESULTS AND DISCUSSION

In this section, the frequency response of the HV phase "V" of themodeled 1.3 MVA, 11-kV/433-V, Dyn1 distribution transformer is obtained under different core conditions which were discussed in previous section.In the simulations reported in this paper, the magnitude of the end to end voltage ratio of the phase winding is considered as the transfer function and the measured frequency range is 100 Hz to 1 MHz.

A. Effect of Core Material (Magnetic Steel)

As discussed in section 3-1, the permeability of M-4 magnetic steelhas higher value comparing to M-5 and M-6magnetic steels, and M-6 magnetic steelhas lower permeability with respect to the others. This leads to $L_{M-4} > L_{M-5} > L_{M-6}$. Therefore, at low frequencies which are mostly affected by the coreinductance, thefrequency response of M-4 magnetic steelwill have greater magnitude in absolute. In other words the attenuation of M-4 will be more than others. Figure. 6 shows this fact.

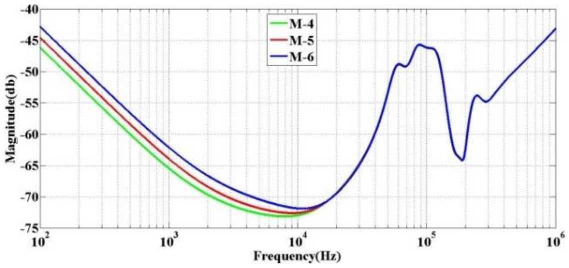


Figure 6. Frequency response trace for phase "V" of the transformer with M-4, M-5 and M-6 core magnetic materials

B. Effect of Core Magnetization

The results presented in Figure 4 proved that directly after disconnecting the transformer from the network, the permeability of the magnetic steel has a high value due to the magnetic after-effect. Over the time the reversible component of magnetization process disappears and the value of the permeability decreases. Thus the inductance of the core will decrease over the time and this leads to shifting up the frequency response to higher absolute values. Figure 7 shows the effect of core magnetization on FRA result.

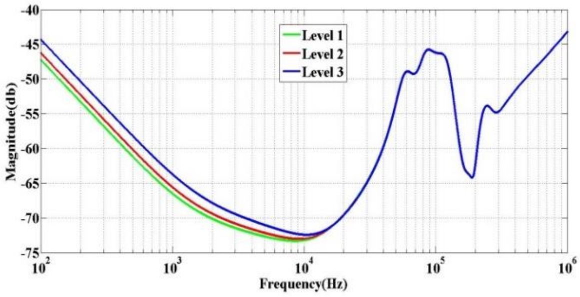


Figure 7. Effect of core magnetization on the frequency response of the phase "V" of the transformer

C. Effect of Core Saturation

As mentioned in section III-C, the saturation of core would decrease the core inductance and therefore, shifting up the frequency response to higher absolute values (Figure.8). The resulting frequency responses in Figure. 8 indicate that the core saturation has considerableeffect on FRA results up to frequency ofabout 20 KHz. Saturated core wouldn't change the resonance value and arrangement, just shifted up the low frequency resonance point to higher frequencies.

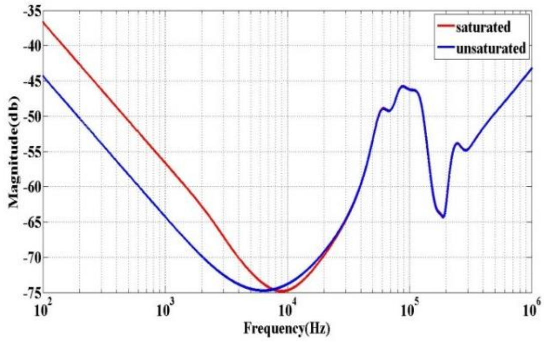


Figure 8. Effect of core saturation on the frequency response of the phase "V" of the transformer

D. Effect of Core Structure

As it was depicted in Figure. 5, the 5-limb core has greater inductance comparing to 3-limb core and thus the frequency response of 5-limb core will be shifted down. Figure 9 shows the FRA traces for the 5-limb and 3-limb cores. Due to the different values of the core inductance in the low frequency region, the FRA results are different. In high frequency region, both frequency response traces have the same values. A notable point is the shifting of the resonance and anti-resonance resonance points around 50-90 kHz to higher frequencies.

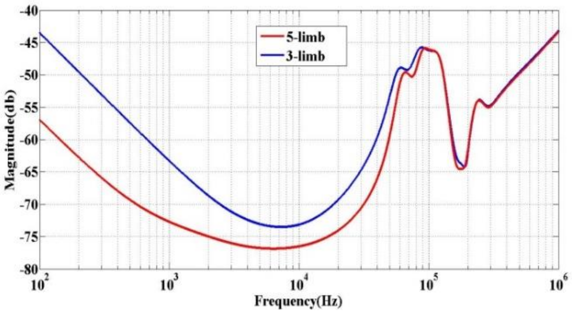


Figure 9. FRA traces of phase "V" for 5-limb and 3-limb cores

V. CONCLUSIONS

In this study, a 3-phase detailed model of a 1.3 MVA, 11-kV/433-V, Dyn1 distribution transformer was used to characterize the core effects on frequency responseof the power transformers.The dependency of the core permeability and the winding resistance to the frequency were considered using the transformer detailed model.The effects of the core magnetic steel, core saturation, core magnetization and core structure on frequency response of the power transformers were analyzed. The simulation results proved that the core magnetic steel affects the FRA signature at low frequencies up to 10 kHz. The magnetization of the core also leads the frequency response trace to shift up at low frequency region.

According to these observations, FRA measurements on transformers may not be performed directly after disconnecting from the network, for avoiding the core magnetization effects. The saturation of core decreases the core inductance and thus the response shifts up to higher absolute values.Finally it was shown that 5-limb core has lower inductance comparing to 3-limb core and thus its FRA signature has more attenuation in the frequency range up to 100 kHz. The information provided is of great importance as a complete diagnosis and fault detection system in power transformers base upon FRA relies on this understanding of the characteristic signatures attained to transformer parts.

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