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HALF-ORDER ANALYTICAL MODELLING OF FERROMAGNETIC SHEET. VALIDATION WITH FINITE ELEMENT SIMULATION

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Abstract – This paper presents a half-order modelling approach applied to a saturated ferromagnetic sheet. Several analytical models are then developed and compared for 1D formulation. In order to identify parameters and valid such models, the saturated ferromagnetic sheet has been simulated using Flux® finite element simulation software.

I. INTRODUCTION

Nonlinearity is a phenomenon which has to be taken into account in diverse applications, e.g. design of electric machines or transformers [1]. Then, this phenomenon cannot be neglected in order to obtain high precision models. Non integer order systems are used to model diffusion in conductive parts of electrical machines as they lead to more compact and knowledge models but also to improve their precision [2]. Nevertheless non integer order models rest valid for linear cases. It is then interesting to study the influence of saturation on such model parameters.

In this article, we first present the linear half-order model of a ferromagnetic sheet deduced from the diffusion equation of the magnetic field. Then, a new formulation taken into account the skin effect and the saturation of the magnetic materials is presented and compared to classical analytical models. Finally, the non linear half-order sheet model is identified and validated from a finite elements simulation.

The studied ferromagnetic sheet is presented in Figure 1. It is characterized by permeability (μ), resistivity (ρ) and surrounded by a n-turn winding.

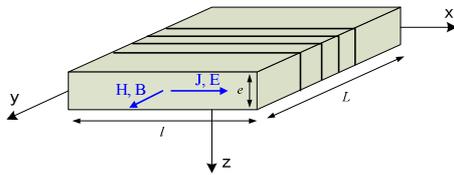


Fig.1. Studied ferromagnetic sheet

II. IMPEDANCE MODELLING IN LINEAR CONDITIONS

II.1. Classical analytical models

Classical analytical model of impedance can be expressed by equation (1) [3].

$$\bar{Z}_{analy} = j\omega \cdot L_0 \cdot \frac{\tanh(\bar{\alpha})}{\bar{\alpha}} \quad (1)$$

with:

$$L_0 = \frac{\mu \cdot n^2 \cdot e \cdot l}{L} \quad \text{and} \quad \bar{\alpha}^2 = j\omega \cdot \frac{1}{\rho} \cdot \mu \cdot \left(\frac{e}{2}\right)^2 \quad (2)$$

L_0 is the DC inductance of the sheet; an integer order approximation of this impedance from serial decomposition of \tanh function can then be used in simulation software.

II.2. Half-order model

From a second-order limited development of \tanh function, another approximation of the analytical impedance is presented introducing half-order systems [4].

$$\bar{Z}_{1/2} = \frac{L_0 \cdot j\omega}{\sqrt{1 + j \cdot \frac{\omega}{\omega_0}}} \quad \text{with} \quad \omega_0 = \frac{1}{\frac{1}{\rho} \cdot \mu \cdot \left(\frac{e}{2}\right)^2} \quad (3)$$

Figure 2 presents a comparison between the analytical expression and its approximation using half-order system. The half-order model is then a good approximation of the analytical result along a wide frequency range, even if a small gap around the cut-off frequency can be noticed.

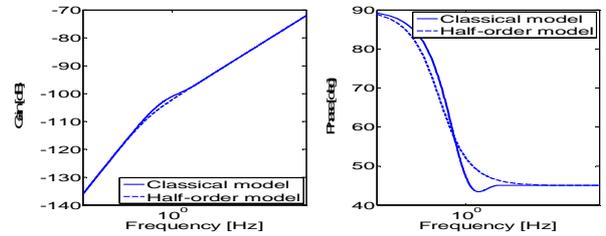


Fig.2. Classical and half-order models of the sheet

III. NON-LINEAR AND NON-INTEGGER MODELLING

III.1. State of art on 1D non-linear models

There are several ways to model impedance in saturated conditions. First of all, we consider that the first harmonic hypothesis is available; therefore, thanks to the method of equivalent permeability used by simulation software, all electrical variables are considered to be sinusoidal.

Classical impedance variations with current and frequency can be represented by equation (4) :

$$\bar{Z}(\omega, i) = L_{static}(i) \cdot j\omega = \left(\frac{L_0'}{1 + k \cdot i^n} + l_\sigma \right) \cdot j\omega \quad (4)$$

where: L_0' , l_σ , k and n are parameters identified from measurements [5]. It is also possible to obtain non-linear impedance model by resolving with severe approximations the non-linear diffusion equation of the electromagnetic field [1]. Nevertheless, these

analytical models are too simple because of the approximative saturation curve. They only allow to characterise the decrease of the DC inductance with current increase.

III.2. Non-linear half-order model

The authors propose a new analytical model of the impedance taking into account frequency phenomena in non-linear conditions. Then, the structure of the model presented in equation (3) remains identical, but parameters L_0 and ω_0 vary with the field current. This model is then described by:

$$\bar{Z}_{1/2}(\omega, i) = \frac{L_0(i) \cdot j\omega}{\sqrt{1 + j \cdot \frac{\omega}{\omega_0(i)}}} \quad (5)$$

We suppose that: $L_0(i) = L_{static}(i)$ with $l_\sigma = 0$ and $L_0' = L_0$. Moreover L_0 and ω_0 are supposed to be linked as $\omega_0(i) = m/L_0(i)$, where m is a parameter to identify (Fig. 5). Finally, the half-order model of saturated impedance is given by (6). It is characterized by three parameters to identify: k , n and m .

$$\bar{Z}_{1/2}(\omega, i) = \frac{\frac{L_0'}{1 + k \cdot i^n} \cdot j\omega}{\sqrt{1 + j \cdot \frac{\omega \cdot L_0'}{m(1 + k \cdot i^n)}}} \quad (6)$$

III.3. Validation with finite element calculations

In order to validate the new model of impedance, finite element simulations were done (Fig. 3). The impedances were calculated over the range of frequency from 0.01 Hz to 1000 Hz. The current flowing in a one turn winding varies from 0.01 A to 20 A, which corresponds to a magnetic field between 0.05 and 100 A/m.

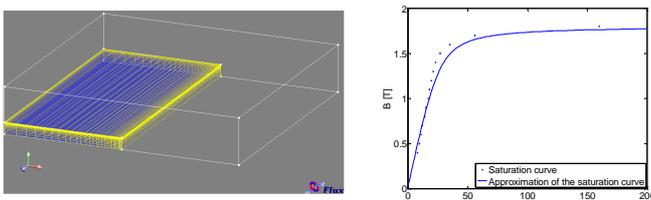


Fig.3. Modelled ferromagnetic sheet with its saturation curve

In Figure 4, the simulation results are shown. Using these data, the set of parameters (k , n , m) of the new model presented in (6) have been identified for one chosen frequency equal to 50 Hz. The identified parameters are given in Table 1.

TABLE I
IDENTIFICATION OF MODEL PARAMETERS

k	n	m
0.0229	1.5969	4.0307e-6

Comparison of the identified model for whole range of frequency with finite element simulations is shown in Figure 6 for two values of field current (0.01 and 20 A). It can be noticed that the model seems to agree with simulations. Then, the asymptote of the impedance is still equal to 10 dB per decade.

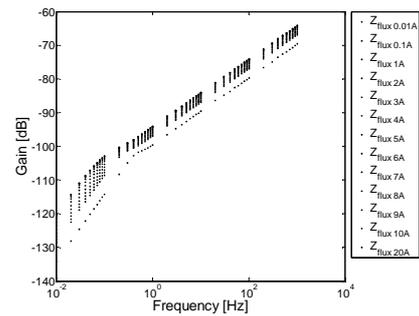


Fig.4. First-harmonic model of the saturated impedance

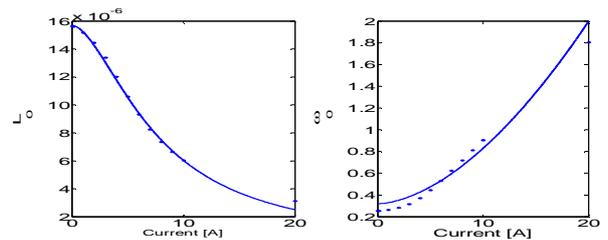


Fig.5. Identified parameters $L_0(i)$ and $\omega_0(i)$ and their approximation

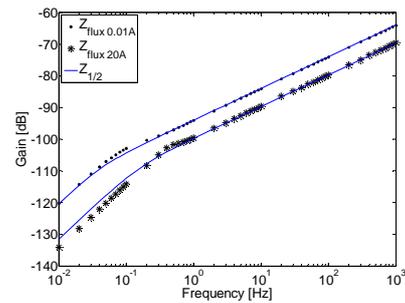


Fig.6. Comparison of the half-order model with the finite element simulations

IV. CONCLUSION

This paper presents a new analytical model of a saturated magnetic sheet which can be described by only 3 parameters which are identified from a finite element simulation. This model corresponds very well with simulations along a wide range of frequencies.

This model will be soon included in the equivalent circuits of a synchronous machine taking into account on the one hand eddy-currents in massive parts of the rotor or rotor bars and, on the other hand, saturation of the magnetic field.

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