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PREISACH HYSTERESIS IMPLEMENTATION IN RELUCTANCE NETWORK METHOD, COMPARISON WITH FINITE ELEMENT METHOD

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Abstract - In this work, an implementation of static magnetic hysteresis in the reluctance network method is presented and its effectiveness is demonstrated. This implementation is achieved by a succession of iterative steps in the form of algorithm explained and developed for simple examples. However it remains valid for any magnetic circuit. The results obtained are compared to those given by finite element method simulation and essentially the effect of relaxation is discussed for a good representation of hysteresis loops.

I. INTRODUCTION

Soft magnetic materials are characterized by non linear and hysteretic B(H) law which is very sensitive to the exciting conditions. This behavior should be considered in electromagnetic devices to achieve precise calculation and optimization. This requires facing two main issues. The first one is to find out a simple but accurate hysteresis model able to describe the hysteresis under the practical working conditions of the material in the magnetic circuit. The second one is to implement the model in a calculation tool in order to compute complex device geometry. Finite Element Method (FEM) and Reluctance Network Method (RNM) are often used to perform that.

In the modeling of the electromagnetic systems, several authors seek to implement the hysteresis in a simple and accessible way. For example in [1], a suitable iterative procedure was proposed to resolve the problems due to the hysteresis integration in FEM: convergence in critical point of hysteresis (near coercive field H_c and remanent induction B_r) and a large iterations number. In [2] and [3], authors are interested in the losses iron calculation using models based on empirical formulas and models of hysteresis applicable to the variable reluctance machines.

The main objective of this work is to implement hysteresis phenomenon in electromagnetic systems computation by RNM via a simple algorithm. The considered hysteresis representation is the Preisach model.

II. RELUCTANCE NETWORK METHOD (MAGNETIC EQUIVALENT CIRCUIT)

The Magnetic Equivalent Circuit (M.E.C.) approach consists in the building of reluctances or permeances network which is representative of the studied magnetic circuit. The network topology is chosen according to geometrical considerations based on the flux tubes general direction knowledge. The definition of the reluctance comes from the integral expressions of the Maxwell's equation in magnetostatics. In another terms, it represents the ratio of the magnetic potential θ and the magnetic flux Φ .

$$R = \frac{1}{P} = \frac{\theta}{\phi} = \int \frac{dl}{\mu \cdot S} \tag{1}$$

Reluctance *R* or permeance *P* depends on the geometry of the elementary magnetic circuit (section S and length dl) and the magnetic material (permeability μ). We can speak then about the variable reluctances if dl, S or μ change during calculation: movement of some parts in actuators, non homogeneity of permeability in electrical machines. Implementation of hysteresis developed in the next section concerns mainly this last fact.

III. HYSTEREIS INTEGRATION IN A RELUCTANCE NETWORK METHOD

To describe the principal of the method and illustrate the different calculation steps, we describe the procedure in form of an algorithm established from the electromagnetic equations and the constituent media laws.

The relation between the induction B, the magnetic polarisation J and the exciting field H can be written as usual:

$$B = \mu_0 H + J(H) = \mu_{ferro} H$$
⁽²⁾

J is described in this case by the static Preisach model [4]:

$$J(t) = \mu_0 \iint_{\alpha > \beta} \rho(\alpha, \beta) \cdot \phi_{\alpha\beta} [H(t)] d\alpha.d\beta$$
(3)

Where $\rho(\alpha,\beta)$ is the Preisach density, $\Phi_{\alpha\beta}$, the cycle operator and α,β its coordinates in the Preisach plane. $\rho(\alpha,\beta)$ is determined using the modified Lorentzian density:

$$\rho(\alpha,\beta) = \frac{k \cdot a^2}{\left(a + \left(\frac{\alpha}{H_c} - b\right)^2\right) \cdot \left(a + \left(\frac{\beta}{H_c} + b\right)^2\right)}$$
(4)

Hc: Coercive field, k: regulating coefficient.

In term of magnetic flux, equation (2) becomes:

$$\phi = B \cdot S = (\mu_0 H + J(H)) \cdot S = \frac{1}{R_0} H \cdot L + J(H) \cdot S$$
(5)

Equation (5) shows that R_{ferro} can be modeled by a constant reluctance R_0 associated to a variable flux source J(H).S, Figure 1.



Fig. 1. Transformation of the variable reluctance R_{ferror}

Thus the magnetic flux can be expressed as:

With

and

 $\phi = \phi_0 + \phi_m$

(6)

(7-a)

$$\phi_0 = \frac{1}{R_0} H \cdot L$$

$$\phi_m = J(H)S \tag{7-b}$$

 ϕ_0 is the magnetic reluctance without magnetization expressed by Kirchoff laws.

Figure 2, summarizes the main steps of the calculation algorithm. For each time step, the program determines the exciting current, ϕ_0 and the magnetic field H. An iterative process based on H relaxation is then performed in order to calculate the instantaneous polarisation.



Fig.2. Algorithm of hysteresis implementation in a RNM

IV. RESULTS AND DISCUSSION

A. Comparison with finite element method

To validate this algorithm, a simple magnetic circuit model is considered as shown in Figure 3.a. It is composed of an inductor and two ferromagnetic materials circuits: MC1 which is assumed to be linear and MC2 which obeys to an hysteresis phenomenon. Its magnetic equivalent circuit can then be established and described by two reluctances as given in Figure 3.b.



R, related to MC1, is a classical reluctance which can be easily calculated knowing the MC1 dimensions and its constant permeability μ .

The electromagnetic device is calcuated by the reluctance network method proposed and also simulated by a twodimensional finite element method (Figure 4), considering hysteresis behavior of CM2 part. FEM computation was achieved thanks to the implementation of hysteresis algorithm proposed in [1]. In the two cases, a sinusoidal current (NI_{max} = 66 A), was taken in the inductor coil and the hysteresis Preisach parameters were: k = 0.25, $H_c = 1000$ A/m, $J_s = 1.3$ T (modified Lorentzian function equation (4) [4]).



Fig. 4. Finite element mesh of the electromagnetic system

Figures 5 and 6, are related to FEM simulation results obtained in CM2 part. They show the exciting current of the magnetic circuits, some obtained local B(t) time evolutions in the middle of CM2 and the corresponding hysteresis loops. These results clearly highlight the trapezoidal shape of B(t) and the shift phase between I(t) and B(t) induced both by hysteresis.



Fig. 5. Flux density time evolution obtained in different elements of the MC2 circuit



Fig. 6. Magnetic hysteresis cycle obtained in different elements of the MC2 circuit

In order to compare this results to those obtain with our RNM approach, the average behavior of the CM2 part is deduced. In Figure 7, the mean of B(t) calculated in all the CM2 elements and the global B(t) given by the magnetic equivalent circuit (RNM) are plotted. The result is remarkable and validates this approach. The small differences observed can be due by the flux leakages which are not considered in the NMR approach.



B. Effect of relaxation

To study the sensitivity of the algorithm to the value of the relaxation parameter ω , the quasi-static magnetic problem is solved with different relaxation values and suitably chosen time steps. If a relaxation value is chosen close to the value 1, the convergence of the process is obtained for a minimum number of iterations (Fig. 8). However, the calculated hysteresis loop is not regular and smooth because a few samples are generated at the critical zones (around coercive field H_c or remanent induction B_r [1] and [5]). The comparison between the hysteresis loops simulated using relaxation parameters ω of 0.90 and 0.50 and 10^{-4} an error tolerance ($\epsilon = 1e$ -4) is shown in Figure 8.



Fig. 8. Hysteresis cycles for two relaxation values (0.5 and 0.9)



Fig. 9. Relaxation factor as a function of iterations number

Figures 8 and 9 present simulation results of hysteresis, with relaxation value ($\omega = 0.90$, $\omega = 0.50$). It is worth to note, that the augmentation of relaxation parameter can accelerate convergence and reduce consuming time but in the other hand, the loop surface is not reproduced accurately during the iteration process.

B. Other applications

In this part we choose another magnetic circuits Figure 10, the first consists of two ferromagnetic materials of different hysteretic comportment and the second is a circuit of which are applied two FM sinusoidal different in frequency.



Fig.10. Other magnetic circuit application

For the first circuit, the characteristics of the hysteresis models are ($H_{c1} = 1000$, $H_{s1}=5000$, $k_1=0.5$, $H_{c2} = 700$, $H_{s2} = 3000$, $k_2 = 0.25$, equation (4)). We notice perfectly the effect of saturation describes by the total flux which is the sum of the two elementary fluxes (Fig. 11).



Fig. 11. Time variations of flux in the first magnetic circuit.

The second circuit two sinusoidal mmf (magneto motrice force) of same amplitude but respectively at 50 Hz and 80 Hz. The magnetic field resulting in the ferromagnetic branch is such represented in Figure 12, and consequently the magnetic flux generated presents a strong saturation in particular for the strong values of the magnetic field Figure 13.



Fig.12. Time variation of magnetic field in ferromagnetic branch (second magnetic circuit)



Fig.13. Time variation of magnetic flux in ferromagnetic branch (second magnetic circuit)

As seen, we can determine by this algorithm the nonlinear behaviour of various magnetic circuits considering the characteristics of the hysteresis cycles of the material they are made of.

IV. CONCLUSION

This work highlighted that the implementation of static hysteresis in reluctances networks, according to the proposed algorithm is not only possible, but gives accurate results. A simple magnetic circuit is used but the approach can be adapted for more complex geometry. To detect importance of relaxation value and time steps number in evaluating hysteresis surface, magneto-static simulations are presented for two relaxation values. Other circuits are analyzed to show the broad possibilities of application of our model. Futur works will be investigated in order to consider dynamic hysteresis models and more complex geometry (actuators or electrical machines).

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