

Eddy currents and hysteresis losses evaluation using dynamic Preisach model

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The present work concerns the evaluation of the eddy currents and hysteresis losses. This is performed using dynamic Preisach hysteresis model coupled with the 2D finite elements calculation. Hysteresis parameters as a, b and Hc are obtained according to the hysteresis loop for two temperatures, one of which can be the ambient temperature, and hysteresis loops for two frequencies are computed and then the proposed model for frequency variations permits the identification of "b" parameter. The first hysteresis loop can be very small as the quasi static case. Eddy currents and hysteresis losses are then computed for various excitation field which allow to a description of total hysteresis loop.

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1. Introduction

Losses evaluation has a great importance for systems dimensioning. The possibility offered by an evaluation losses tool at the design phase of an electromagnetic device is a considerable contribution for optimizing its dimensioning and operation. In magnetic materials they are two nature losses, which are dependent, hysteresis and eddy currents one. A method of evaluation losses is based on the Preisach model. The model has the capability to introduce the frequency effects on the hysteresis loop, through the modified Lorentz function coefficient which is in our case "b" coefficient. The basic method uses the hysteresis loops obtained for two known frequencies. Eddy currents and hysteresis losses of an induction device are then computed using dynamic Preisach hysteresis model associated to finite elements calculation.

2. Coupled electromagnetic-magnetization 2D equation

The problem studied considering magneto dynamic hypothesis permits the evaluation of total losses of an induction device as eddy current and hysteresis one. Electromagnetic equation integrating material magnetization is given as following:

$$\vec{\text{rot}}[\vec{\text{rot}}(\vec{A})] + \sigma\mu_0 \frac{\partial \vec{A}}{\partial t} = \mu_0 [\vec{J} + \vec{\text{rot}}(\vec{M})] \quad (1)$$

\vec{A} : Magnetic vector potential, \vec{J} : Source current density [A/mm²], σ : Electric conductivity [Ωm]⁻¹, \vec{M} is the magnetization [A/m]

Losses evaluation is with a great importance for systems dimensioning.

The studied problem concerns the resolution of the previous electromagnetic equation in [x,y] plan with transient harmonic hypotheses. The integration of dynamic

Preisach model in finite elements calculation undertaken to compute hysteresis loop is performed for different excitation field magnitude.

3. Scalar Preisach model

In the Preisach model, it is considered that the material is composed by magnetic entities having an elementary cycle depicted in figure (1) [1], [2],

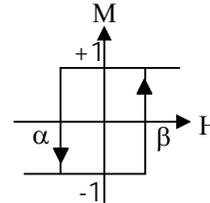


Fig. 1. Elementary Cycle of a magnetic entity.

Where M is the magnetization, H : Excitation field, α : Flip up field M=+1, β : Flip down field M=-1.

The global magnetization is given by the expression (3) below:

$$M(t) = \iint_{S_+} \rho(\alpha, \beta) d\alpha d\beta - \iint_{S_-} \rho(\alpha, \beta) d\alpha d\beta \quad (2)$$

Where, $\rho(\alpha, \beta)$ is the Preisach density defined in the domain $S = \{\alpha \geq \beta, \beta \geq -H_s, \alpha \leq H_s\}$, symmetrical to the straight $\alpha = -\beta$ and limited. in the (O, α , β) plan, the "S" is a triangle. S₋ and S₊ represents respectively the entities with a low and high saturation state. L(t) is a time dependent border.

Many functions are used like Preisach density. In this paper, the modified Lorentz function is considered [1]. It is given by the following equation:

$$\rho(\alpha, \beta) = \frac{Ka^2}{\left[a + \left(\frac{\alpha}{H_c} - b \right)^2 \right] \left[a + \left(\frac{\beta}{H_c} + b \right)^2 \right]} \quad (3)$$

H_c is coercive field, K : normalization coefficient, a : positive value, $b \in [1, H_s/H_c]$.

4. Galerkin’s weighted residual

The integral formulation exploiting the Galerkin method with applying Green theorem is given by:

$$\sum_{j=1}^N \left[\iint_{\Omega} \mu_0 \sigma \phi_i \phi_j dx dy \right] \frac{\partial A_j}{\partial t} + \sum_{j=1}^N \left[\iint_{\Omega} \left(\frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x} + \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y} \right) dx dy \right] A_j \quad (4)$$

$$= \iint_{\Omega} (\phi_i \mu_0 J) dx dy + \iint_{\Omega} \mu_0 \phi_i \left(\frac{\partial M_y}{\partial x} - \frac{\partial M_x}{\partial y} \right) dx dy$$

N : element number, ϕ_i and ϕ_j are shape functions at i and j nodes.

The algebraic system obtained is then given by:

$$[K] \left\{ \frac{dA}{dt} \right\} + [M][A] = [F] + [G] \quad (5)$$

With:

$$K_{ij} = \iint_{\Omega} \sigma \mu_0 \phi_i \phi_j dx dy$$

$$M_{ij} = \iint_{\Omega} \left(\frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x} + \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y} \right) dx dy$$

$$F_i = \iint_{\Omega} \mu_0 \phi_i J dx dy, \quad G_i = \iint_{\Omega} \mu_0 \left(\frac{\partial M_y}{\partial x} - \frac{\partial M_x}{\partial y} \right) \phi_i dx dy$$

$\frac{dA}{dt}$ is discretised using Euler scheme:

$$\frac{dA}{dt} = \frac{A^{t+1} - A^t}{\Delta t} \quad (6)$$

Δt is the step time, A^{t+1} : Unknown value at time $t+1$, A^t : Unknown value at time t .

5. Computation procedure and application

At each step, the computed global magnetic field H_{ti} using finite element code, is decomposed into two parts: a

demagnetizing field H_{di} and an hysteresis model applied field H_{ai} [3].

The computation procedure is described bellow:

- Initialisation: $k = 1, i = 1, \varepsilon$: Given Precision
 - 2. Fixed J_k and M_{1i}
 - 3. Computation of A_i with $J_k = 0$
 - 4. Computation of flux density B_i
 - 5. H_{di} calculation
 - 6. Computation of A_i with $J_k \neq 0$
 - 7. Computation of flux density B_i
 - 8. H_{ti} calculation
 - 9. Computation of $H_a = H_{ti} - H_{di}$
 - 10. Relaxation $H_{ai} = H_{ai-1} + w (H_{ti} - H_{ai-1})$
 - 11. Computation of Magnetization M_2 , with Preisach model
 - 12. Determination of Magnetization direction M_i
 - 13. Evaluation of $\tau = \mu_0 |M_{2i} - M_{1i}|$
- if $\tau < \varepsilon$ convergence: $k = k + 1$ and $i = i + 1$ go to 2, else $i = i + 1$ go to 3

6. “b” coefficient model integrating frequency

The law of variation of “b” according to the frequency is as follows:

$$b(t) = b_{dc} (1 + \alpha_f f^{\beta_f}) \quad (7)$$

b_{dc} : is the value of “b” in the quasi-static case

α_f and β_f are a coefficients without dimension

b_{dc} , α and β is determined as follows:

b_{dc} is in experiments given in the quasi-static case α and β are determined while knowing identifying “b” parameter for two hysteresis loops at two different frequencies.

Let us suppose that b_1 and b_2 are values of “b” parameter, respectively at frequencies f_1 and f_2 , on the basis of formula given in (7):

That is to say:

$$b_1' = \frac{b_1}{b_{dc}}, \quad b_2' = \frac{b_2}{b_{dc}}, \quad f' = \frac{f_1}{f_2}$$

$$\alpha = \frac{\left[\frac{b_1' - 1}{b_2' - 1} \right]}{\left[f_1' \right]^{\beta}} \quad (8)$$

$$\beta = \frac{\text{Log} \left[\frac{b_1' - 1}{b_2' - 1} \right]}{\text{Log} \left[f_1' \right]} \quad (9)$$

The curves given in (Fig. 2) show the effect of the of the frequency variation on the hysteresis loop at the ambient temperature. We can note, of share the effect of this variation on the coercitive field that the effect of the frequency appears perfectly integrated.

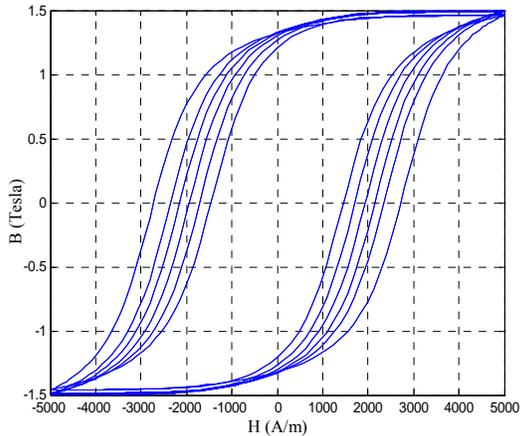


Fig. 2. Hysteresis loops for different frequency ($f=50, 100, 150, 200, 250, 350$ Hz).

Curves given in (Fig. 3) represent the effect of the temperature on the hysteresis loop at a frequency about 200 Hz.

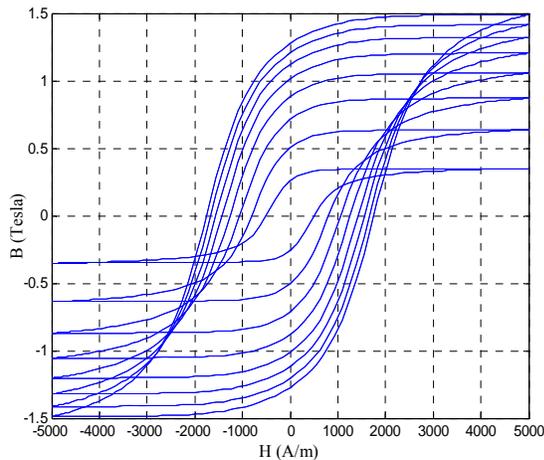


Fig. 3. Hysteresis loops variation with temperature for frequency $f=200$ Hz.

Curves given in (Fig. 4) represent the effect of the frequency on the hysteresis loop 200°C.

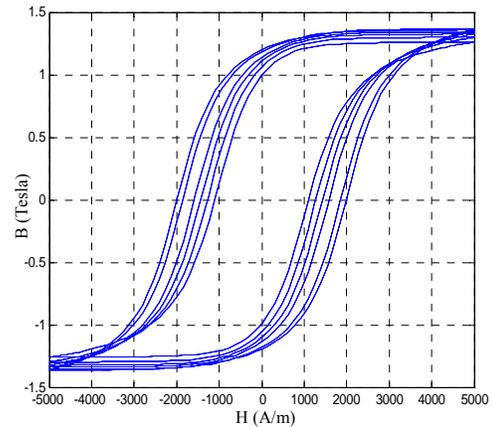


Fig. 4. Hysteresis loops for different frequency at 200 °C.

7. Finite elements analysis

The application considered in the current work is an induction device with its physical characteristics early used in reference [2]: Physical characteristics are as saturating field: $H_s=5000$ A/m, Coercitive field: $H_c=1000$ A/m, flux density to saturation: $B_s=1.5$ T.

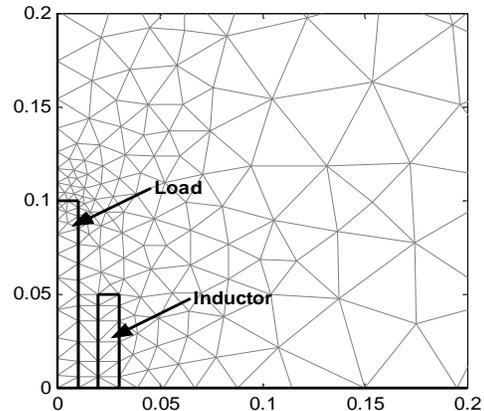


Fig. 5. Solving Domain.

The convergence criteria used in reference [2] is based on the precision of the applied magnetic field, as for the criteria used in this study, it is defined by $|(M_2 - M_1)|\mu_0 \leq \epsilon$, where M_1 is the magnetization calculated by using the finite elements code and M_2 is the magnetization obtained starting from the Preisach hysteresis model. The criteria of convergence considered have the advantage to ensuring the convergence of the algorithm at the first iteration [3]. The eddy currents losses are calculated, by using the equation below (10):

$$P_{CF} = \frac{1}{T_c} \int \left[\iiint (DP_{CF}) dv \right] dt \quad (10)$$

The hysteresis losses are calculated by using the following expression (11):

$$P_{hys} = \frac{1}{T_c} \int \left[\iiint [DP_{hys}] dv \right] dt \quad (11)$$

Where

$DP_{CF} = \sigma \cdot \left(\frac{\partial \vec{A}}{\partial t} \right)^2$ is the eddy currents density losses.

$DP_{hys} = \vec{H} \cdot \frac{\partial \vec{B}}{\partial t}$ is the hysteresis density losses.

H : excitation magnetic field [A/m],

T_c : current density period [s],

B : flux density [T],

$J_{max} = 8 \cdot 10^5$ [A/m²].

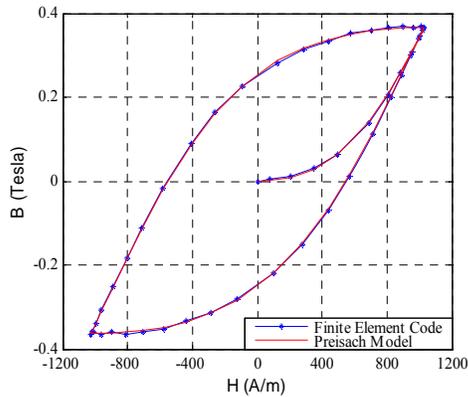


Fig. 6. Hysteresis loops with excitation current density $J_{ex} = 0.2 * J_{max}$

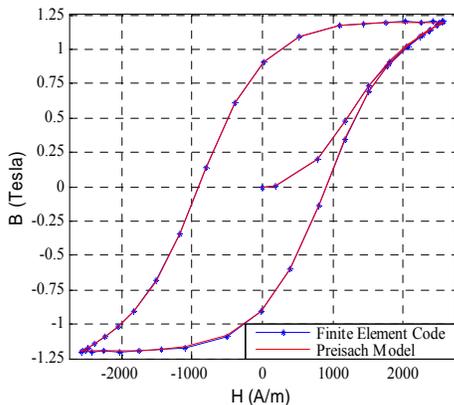


Fig. 7. Hysteresis loops with excitation current density $J_{ex} = 0.5 * J_{max}$

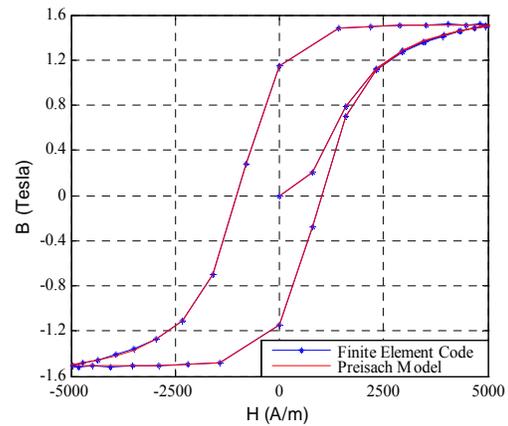


Fig. 8. Hysteresis loops with excitation current density: $J_{ex} = J_{max}$.

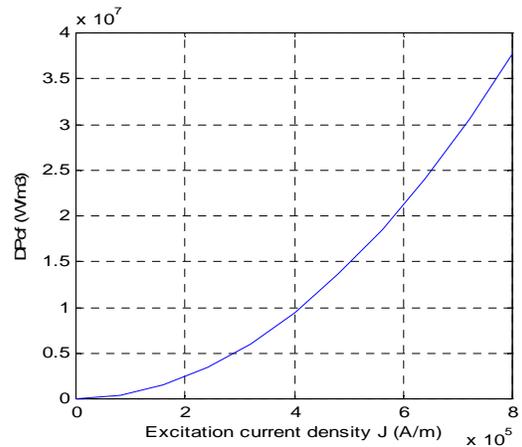


Fig. 9. Eddy current density losses variation with excitation current density.

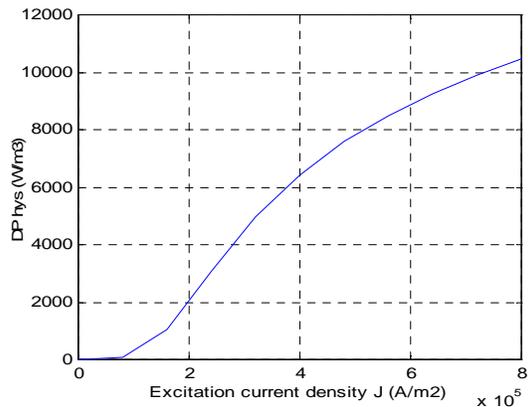


Fig. 10. Hysteresis loss density variation with excitation current density

The results given in figures (6), (7) and (8) show a good integration of the model in the finite elements code. The results given in figure (9) represent the eddy currents

losses according to the operate current density. The losses appear like proportional to the square of the current density. The results given in Fig. 10 represents the hysteresis losses, these losses tend to be saturated according to the increase in the density of the operate current.

8. Conclusion

The calculation of Preisach hysteresis loop is performed for different values of frequencies, where the increase of hysteresis area can be note.

The identification method of hysteresis parameters depending of frequency is also presented.

The eddy current losses according to the source current density appear like to the square of the source current density and the hysteresis losses tend to be saturated when the source current density increases.

The results obtained are in good agreement with the theory. Taking into account the eddy current and hysteresis losses permit an optimal device dimensioning and this according to desired working point.

References

- [1] F. Henrotte, A. Nicolet, F. Delincé, A. Genon, and W. Legros, "Modeling of ferromagnetic materials in 2D finite element problem using Preisach's model," *IEEE Transactions on Magnetics*, **28**(5), September 1992.
- [2] Y. O. Amor, M. Féliachi, and H. Mohellebi "A New Convergence Procedure for the Finite Element Computing Associated to Preisach Hysteresis Model," *IEEE Transactions on Magnetics*, **36**(4), July 2000.
- [3] S. H. Ould Ouali, H. Mohellebi, R. Chaibi and M. Féliachi, "2D Finite Elements Modeling of Magnetic Material Taking into account Its History: Application to an Induction Heating System," *ISEM'2005*, BAD GASTEIN, Vienna Magnetic Group Reports, Editors: H. Pfutzner & E. Leiss, ISBN 3-902105-00-1.

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