Journal of ELECTRICAL ENGINEERING, VOL. 55, NO. 11-12, 2004, 319–323

AN INVERSIBLE MODEL FOR HYSTERESIS CHARACTERIZATION AT CONSTANT FLUX AMPLITUDE

Damien Halbert — Erik Etien — Gérard Champenois *

A new model, available in the case of constant flux amplitude is presented. It allows to consider global closed loop modeling of the phenomenon. The model obtained is linear with its parameters, and their estimation is then simplified and done using linear least square algorithm. An application to a single phase transformer is proposed in order to validate the proposed method.

K e y w o r d s: hysteresis model, Least square method, flux estimation, magnetic circuit

1 INTRODUCTION

Magnetic hysteresis modeling has attracted the interest of researchers for many years. Among the best known methods, one will quote the methods separately describing higher and lower branches of the cycle as well as the rules of passing from one to the other [5].These methods are simple and allow an easy calculator computation [25]. On the other hand, the Preisach model [22] and its derivatives are known as being one of the most powerful methods currently used [17]. Based on the elementary hysterons association, this method uses repartition functions which allow to approximate the hysteresis comportment via analytic [18],[19] or numeric methods [20], [21].

Another convenient method is the Jiles-Atherton model. Based on physical consideration, it decomposes the total magnetization into a sum of reversible and irreversible components [6]. One of the advantages of this model is its reduced number of parameters (five in classical configuration) but their estimation needs particular experimental tries [8] and makes the identification process difficult [7]. Many methods have been proposed to circumvent theses problems as ones minimizing quadratic criterium [10] or others using genetic algorithms [9].

In this communication we show that, in the particular case of a constant flux amplitude, anhysteretic magnetizing equation used in Jiles-Atherton model may describe the hysteretic behaviour. The model obtained may be represented by a closed loop system. It allows to model only major loops and simplifies parameters identification which may be performed by a simple linear least square algorithm [12]. Moreover, the obtained model is reversible and permits to rebuild the magnetic field knowing the magnetization. This model is used in the case of a single phase transformer magnetic core study and an alternative to direct induced voltage integration in the presence of offset during measurement is presented.

2 HYSTERESIS MODEL

2.1 Closed loop model

By definition, anhysteretic magnetization curve M_{an} is the global equilibrum state which would be achieved without pinning sites. This curve represents the skeleton around which hysteresis develops. In [6], the anhysteretic function is modelled using a Langevin function

$$M_{an}(H) = M_s\Big[coth\Big(\frac{H+\alpha M}{a}\Big) + \frac{a}{H+\alpha M}\Big]. \qquad (1)$$

Where H is the magnetic field, M is the magnetization and α, a, M_s, parameters to be determined.

Because this curve is independent of prior history, it cannot be, theoretically, used alone in order to describe hysteresis behavior.

However, as shown in [6], equation (1) can give rise to an elementary form of hysteresis loop if the coefficient α is sufficiently large. Figures 1 and 2 show results provided in [6] where equation (1) is simulated with two different values of parameter α. For these simulations, the magnetization M_{an} is replaced by M:

$$M(H) = M_s\Big[coth\Big(\frac{H+\alpha M}{a}\Big) + \frac{a}{H+\alpha M}\Big]. \qquad (2)$$

We see that, equation (2), classically used to describe anhysteretic magnetization can also be used to describe major loop in magnetic materials under correct parameters setting.

For our case, we propose to use a model near from equation (2) in order to model the major loop of a magnetic circuit and so we consider a more convenient expression near from [15]:

$$M(H) = \frac{2}{\pi} M_s\, tanh\Big[\frac{(H+\alpha M)}{H_p}\Big]. \qquad (3)$$

* Laboratoire d'Automatique et d'Informatique Industrielle, France, E-mail: etien@esip.univ-poitiers.fr, champenois@esip.univ-poitiers.fr

ISSN 1335-3632

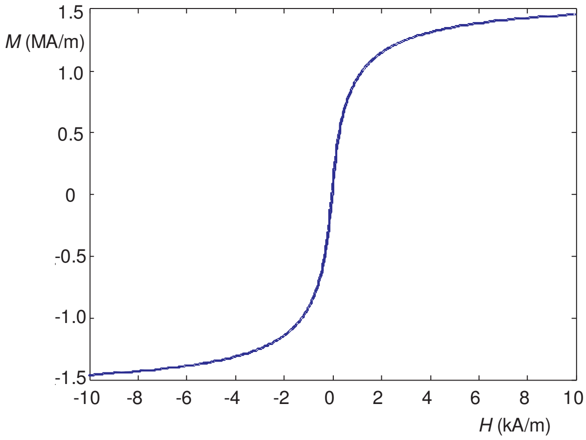

Fig. 1. Solution of equation (2) with parameters: $M_s = 1.6 \times 10^6 A/m\,,\ a = 1100A/m\,,\ \alpha = 1.6 \times 10^{-3}\,.$

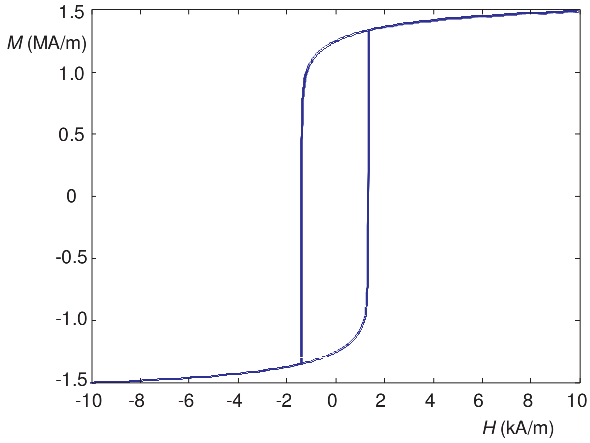

Fig. 2. Solution of equation (2) with parameters: $M_s = 1.6 \times 10^6 A/m\,,\ a = 1100A/m\,,\ \alpha = 4 \times 10^{-3}\,.$

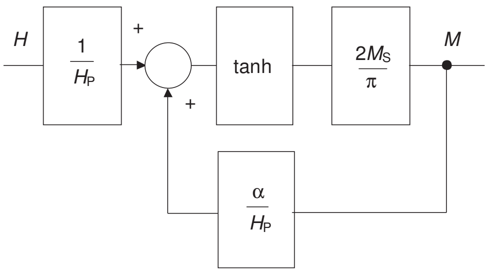

Fig. 3. Closed loop representation of equation (3).

In fact, the use of positive feedback in order to characterize the hysteresis phenomenon was first proposed by Weiss [23], [24] in 1906. Weiss assumed that a nonlinear monotone law combined with a positive feedback can be transformed into a non-monotone law and can then generate hysteresis. Hysteretis behaviour may also be modelled by a closed loop system where the non linear function $f(u)$ has to be chosen in order to describe the cycle shape at best. For example, in electromagnetic applications, different functions may be used depending of the magnetic material used (Ferrites or steel laminations).

In the following part, an identification procedure based on a linear least square algorithm is presented in order to estimate model parameters.

2.2 Parameter estimation

Let us consider a magnetic matter excited with a magnetizing current i_H which causes the flux ϕ. The sampling representation of i_H and ϕ are denoted:

$$i_{H_n} \quad \text{and} \quad \phi_n \quad 1 \le n \le N \tag{4}$$

and N represents the number of samples.

From general closed loop representation (Fig. 3), the following model may be proposed:

$$\phi_k = K_3 \tanh\left[K_1 i_{H_k} + K_2 \phi_{k-1}\right]\,. \tag{5}$$

In this formulation ϕ_k and i_{H_k} are respectively samples of flux and current taken at time $t = k.T_e$ (with T_e the sample period). ϕ_{k-1} is the previous sample taken at $t = (k-1).T_e$. In our model we choose the function $f(x) = tanh(x)$ for two main reasons. $f(x)$ is an odd function and may be consequently used on all the domain $H \in [-\infty; +\infty[$.

$f(x)$ asymptotically leads to ± 1. To describe the asymptotic direction, the saturation level will be directly fixed by K_3. This particularity will simplify the identification procedure which will be presented in the following part.

Consider K_3 as a known parameter. We form the intermediary variable ϕ' defined by:

$$\phi' = atanh\left(\frac{\phi}{K_3}\right). \tag{6}$$

The modified model can be written:

$$\hat{\phi}'_k = \hat{K}_1 i_{H_k} + \hat{K}_2 \phi_{k-1}\,, \quad 2 \le k \le N\,. \tag{7}$$

And:

$$\hat{\phi}'_k = \left[\, i_{H_k} \quad \phi_{k-1} \,\right] \cdot \begin{bmatrix} \hat{K}_1 \\ \hat{K}_2 \end{bmatrix} = \underline{\varphi}^\top \cdot \underline{\hat{\theta}'}\,, \quad 2 \le k \le N\,. \tag{8}$$

Equation (8) may be expressed under matrix form:

$$\underline{\hat{\phi}'} = P \cdot \underline{\hat{\theta}'}\,, \tag{9}$$

$\underline{\hat{\phi}'}$ is the vector containing the samples of the estimated output, $\underline{\hat{\theta}'}^\top = \left[\hat{K}_1 \quad \hat{K}_2\right]$ is the vector containing parameters to be determined, $P \in \Re^{N\times 2}$ is a matrix equal $P = \left[\underline{i_H} \quad \underline{\phi}_{-1}\right]$ where $\underline{i_H} \in \Re^{N-1}$ and $\underline{\phi}_{-1} \in \Re^{N-1}$ are vectors defined by:

$$\underline{i_H} = \begin{bmatrix} i_{H_2} \\ \cdot \\ \cdot \\ \cdot \\ i_{H_N} \end{bmatrix} \quad \text{and} \quad \underline{\phi}_{-1} = \begin{bmatrix} \phi_1 \\ \cdot \\ \cdot \\ \cdot \\ \phi_{N-1} \end{bmatrix}. \tag{10}$$

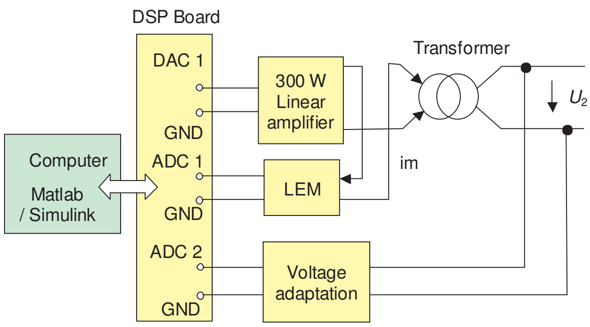

Fig. 4. Experimental plant.

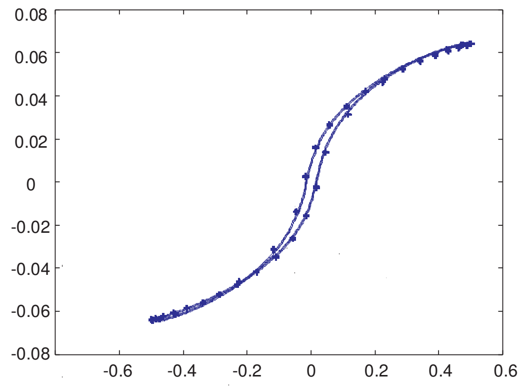

Fig. 5. Hysteresis cycles at 0.1 Hz (solid line) and 5 Hz (+).

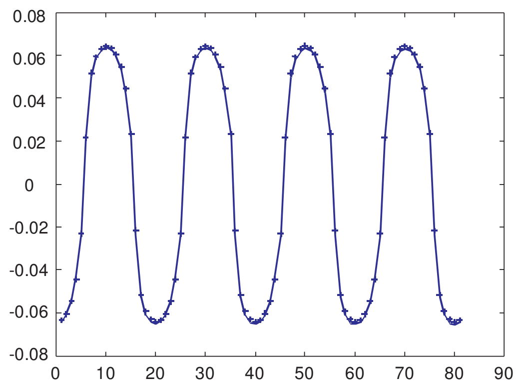

Fig. 6. Measured flux (solid line) and estimated flux (+), f = 0.1 Hz

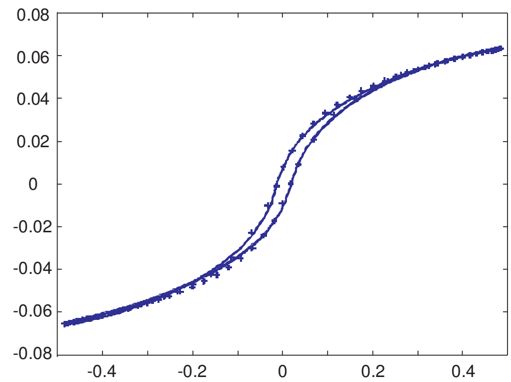

Fig. 7. Measured hysteresis (solid line) and estimated hysteresis (+), $f = 0.1$ Hz

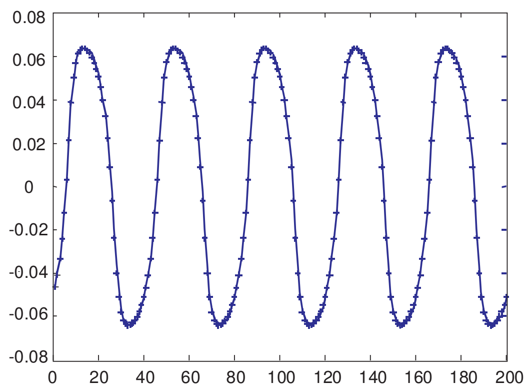

Fig. 8. Measured flux (solid line) and estimated flux (+), $f = 5$ Hz

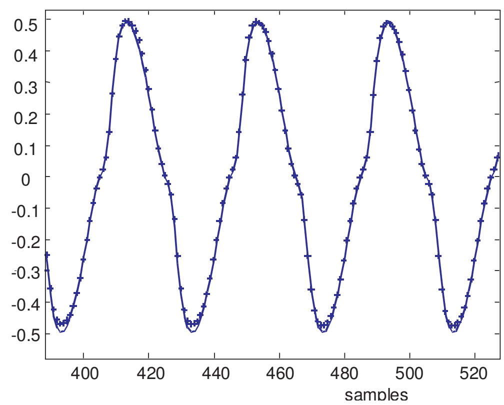

Fig. 9. Measured current (solid line) and estimated current (+), $f = 5$ Hz

$\underline{\hat{\theta}'}^{\top}$ is obtained by the Least Square solution:

$$\underline{\hat{\theta}}_{LS}^{\top} = \left(P^{\top}P\right)^{-1} P^{\top}\underline{M'} \tag{11}$$

with

$$\underline{i_H}'^{\top} = \left[\, i'_{H_2} \quad \dots \quad i'_{H_{N-1}} \,\right]. \tag{12}$$

Consequently and if K_3 is known, parameters estimation may be performed via a Linear Least Square Algorithm.

In our particular case, the choice of the non linear function $f(x) = \tanh(x)$ allows us to determine an value of K_3 directly from the measured data. Define ϕ_{max} as the maximum value of the measured magnetization ϕ. Then, the value of parameter (K_3) is equal to:

$$K_3 = \phi_{\max}\,. \tag{13}$$

2.3 Application

Tests are realized with a 110 V/6 V, 3.2 VA transformer and a digital signal processor TMS320C32 is used

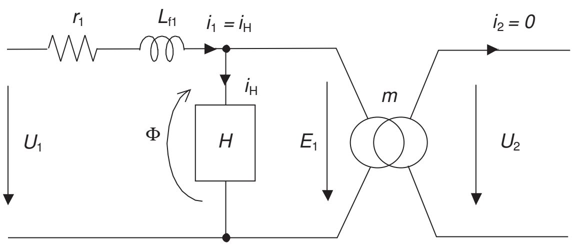

Fig. 10. Equivalent diagram of single phase transformer.

to generate the supply voltages through a linear amplifier. The primary current and the secondary voltage are measured and the flux is estimated from:

$$\phi(t) = \phi_o + \int u_2(\tau)\mathrm{d}\tau \,. \qquad (14)$$

The experimental plant is shown on Fig. 4.

In order to estimate model parameters, we use data stemmed from 0.1 Hz excitation at sample time T_e = 0.1 ms. These data are compared with those obtained for 5 Hz excitation to show that, in low frequency, the cycle is not deformed (Fig. 5) due to a weak influence of eddy currents [13]. This property will be used to validate the estimated model with data different from those used in the identification procedure.

From Fig. 5, initial value $K_3 = 0.08$ is found, the estimation procedure provided following results:

$$K_1 = 0.719\,,\; K_2 = 11.75\,,\; K_3 = 0.08\,. \qquad (15)$$

Figures 6 and 7 show respectively the estimated magnetic flux obtained at the model output and the estimated hysteresis cycle. In order to validate the model (5), it is excited with $5Hz$ current data. Figure 8 show the magnetic flux obtained at the model output. The model obtained permits a good magnetic flux estimation at constant amplitude with respect to hysteresis global behavior.

An interesting property of model (5) is its inversibility. Indeed, knowing the flux, the current i_H may be estimated with the following equation:

$$i_{H_k} = \frac{1}{K_1}\left\{\mathrm{atanh}\Big(\frac{\phi_k}{K_3}\Big) - K_2\phi_{k-1}\right\} \,. \qquad (16)$$

Parameters (15) are used to simulate the inverse model (16) excited with $5Hz$ flux excitation stemmed from equation (14). Results are presented on Fig. 9. This property may be used, for example, to estimate hysteresis and eddy currents contributions [14].

3 FLUX ESTIMATION WITHOUT INTEGRATION

Direct integration of induced voltage at low frequency generates a lot of problems. Indeed, at constant U/f ratio, voltage levels are very small and the least offset in the measurements will cause serious drifts. This problem is well known by researchers working on induction motors sensorless control. The loose of performance that occurs is, at present, one of principal themes of research. An alternative to direct integration may be interesting from this point of view.

In practical cases, induction motors for example, the secondary circuit is not accessible and only primary measurements are available. To illustrate this, we consider the transformer equivalent diagram given in Fig. 10, where i_1 is the primary current, u_1 is the supply voltage, i_H is the magnetizing current, m is the transformation ratio, ϕ is the total magnetic flux, u_2 is the secondary voltage and E_1 the induced voltage defined by:

$$E_1 = -\frac{\mathrm{d}\phi}{\mathrm{d}t}\,. \qquad (17)$$

The primary parameters are the resistance r_1 and the leakage inductance l_{f_1}. The latter will be neglected is this work. In the particular case of no-load condition we have $i_1 = i_H$. Our hysteresis model is denoted H.

For primary data based flux estimation, equation(14) may be modified as:

$$\phi(t) = \phi_o + \int u_2(\tau)\mathrm{d}\tau = \phi_o + \int m\,E_1(\tau)\mathrm{d}\tau\,. \qquad (18)$$

From 5 Hz data, an 1 % offset is added to primary current. The calculated flux is shown on Fig. 11. In comparison, the flux is estimated from the identified model excited with the modified current. The two flux are compared on Fig. 12.

We see that, the flux estimation is not affected by offset when direct integration provide drift even if its level is small in front current ones. Integration (18) is performed only during identification procedure where a great attention can be brought to offsets on measurements (in laboratory for example). The obtained model may also be used in order to find the flux knowing primary current without any integration. Then the hysteresis model is an efficient way to estimate flux component in magnetic core at low frequencies [13].

4 CONCLUSION

A simplified model of hysteresis has been presented. Based on the anhysteretic equation and available at constant flux amplitude, it permits simply to find parameters via a linear least square algorithm. Experimental results have been shown on a single phase transformer and an application to flux estimation allows to propose an alternative to direct integration of induced voltages. This simple model could be used in the case of systems functioning at low frequency and constant or regulated amplitude flux. Of course, use at elevated frequencies implies to take into account iron losses in order to obtain a complete model.

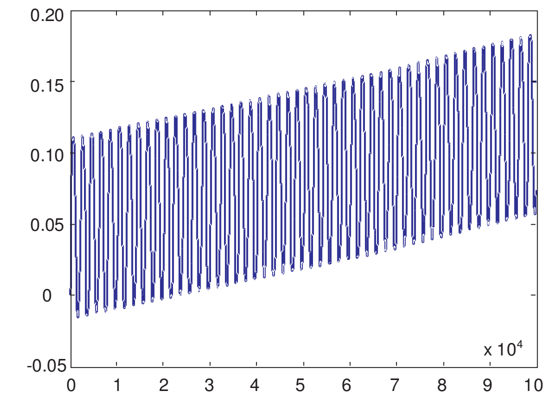

Fig. 11. Calculated flux with 1% offset on primary current.

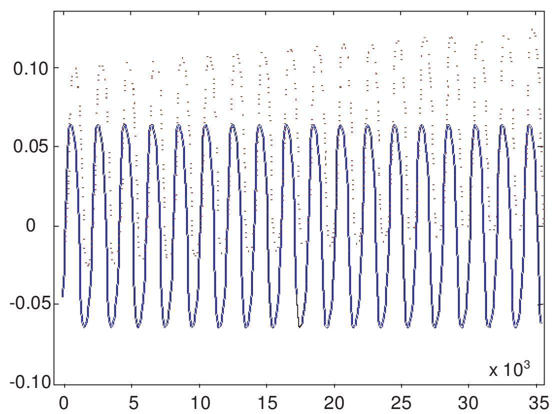

Fig. 12. Calculated (dashed line) and estimated (solid line) flux with 1 % offset on primary current

References

[1] JILES, D. C.: Introduction to Magnetism and Magnetic Materials, Chapman and Hall, London, 1991.

[2] ABUELMA'ATTI, M. T.: A Simple Model for the Transformer Magnetizing Characteristic, Electrical Machine and Power Systems **16** (1989), 127–132.

[3] KEYHANI, A.—TSAI, H.: IGSPICE Simulation of Induction Machines with Saturable Inductances, IEEE Trans Ind. Appl **4** No. 1 (1989), 180–189.

[4] FAIZ, J.—SEIFI, A. R.: Dynamic Analysis of Induction Motors with Saturable Inductances, Electric Power System Research **34** No. 3 (1995), 205–210.

[5] ZAHER, A.—FAROUK, A.: Analog Simulation of the Magnetic Hysteresis, IEEE Transaction on Power Apparatus and Systems **5** (1983).

[6] JILES, D. C.—ATHERTON, D. L.: Theory of Ferromagnetic Hysteresis, Journal of Magnetism and Magnetic Material **61** (1986), 48–60.

[7] LEDERER, D.—IGARASHI, H.—KOST, A.—HONMA, T.: On the Parameter Identification and Application of the Jiles-Atherton Hysteresis Model for Numerical Modelling of Measured Characteristics, Trans. on Magnetics **35** No. 3 (1999), 1211–1214.

[8] JILES, D. C.—THOELKE, J. B.—DEVINE, M. K.: Numerical Determination of Hysteresis Parameters for the Modeling of Magnetic Properties Using the theory of Ferromagnetic Hysteresis, Trans. on Magnetics **28** No. 1 (1992), 27–35.

[9] WILSON, P. R.—ROSS, J. N.—BROWN, A. D.: Optimizing the Jiles-ATherton Model of Hysteresis by a Genetic Algorithm, Trans. on Magnetics **37** No. 2 (2001), 989–993.

[10] KIS, P.—IVANYI, A.: Parameter Identification of Jiles-Atherton Model with Nonlinear Least Square Method, Proceedings of HMM 2003, Salamanca, Spain, 28-30 May 2003.

[11] JILES, D. C.: Modelling the Effects of Eddy Currents Losses on Frequency Dependent Hysteresis in Electrical Conducting Media, Trans. on Magnetics **30** No. 6 (1994), 4326–4328.

[12] ETIEN, E.—RAMBAULT, L.: Hysteresis modeling : A closed loop approach, Monréal, Canada, August 2002. Electrimac's.

[13] ETIEN, E.—RAMBAULT, L.: Estimation of Magnetic Flux at Low Frequencies, Proceedings of EPE 2003, Toulouse, France, 02-04 September 2003.

[14] ETIEN, E.—CHAMPENOIS, G.: A Current Estimator Based Model Describing Magnetic Material Comportment at Constant Level Flux, Submitted for publication in ISIE 2004, Ajaccio, France, 04-07 May 2004.

[15] BARANOWSKI, J.: A Modification of the Jiles-Atherton Model, Kwartalnik Elektroniki Telekomunikacji **40** No. 1 (1994), 1–20.

[16] TAKACS, J.: A Phenomenological Mathematical Model of Hysteresis, International Journal for Computation and Mathematics in Electrical and Electronic Engineering **20** No. 4 (2001), 1002–1014.

[17] REPETTO, M.—BOTTAUSCIO, O.—CHIAMPI, M.—CHIARABAGLIO, D.—RAGUSA, C.: Ferromagnetic Hysteresis and Magnetic Field Analysis, International Compumag Society Newsletter **6** No. 1 (1999), 3–7.

[18] KEDOUS-LEBOUC, A.—ROUVE, LL.—WAECKERLE, Th.: Application of Preisach Model to Grain Oriented Steels: Comparison of Different Characterizations for the Preisach Function, IEEE Transactions on Magnetics **31** No. 6 (1995), 3557–3559.

[19] DELLA TORRE, E.—VAJDA, F.: Identification of Parameters in an Accomodation Mode, IEEE Transactions on Magnetics **30** No. 6 (1994), 4371–4373.

[20] MAYERGOYZ, I. D.—ADLY, A. A.: A New Vector Preisach-Type Model of Hysteresis, Journal of Applied Physic **73** No. 10 (1993), 5824–5826.

[21] BERTOTTI, G.: Hysteresis in Magnetism, 1998.

[22] MAYERGOYZ, I. D.: Mathematical Model of Hysteresis, Springer, 1991.

[23] WEISS, P.: Compt. Rend. **143** (1906), 1136.

[24] WEISS, P.: L'hypothèse du champ moléculaire et la propriété ferromagnétique, J. Physique **6** (1907), 661–690.

[25] SUBRAHMANYAM, V.: Representation of Magnetisation Curves by Exponential Series, Proc. IEE **121** No. 7 (1974), 707–708.

Received 19 November 2003

Damien Halbert was born in France in 1978. He prepares for the PhD degree in the laboratory of Automatic of Poitiers. His research interests application of identification techniques for hysteresis modeling and characterization of magnetic cores for industrial applications.

Erik Etien was born in France in 1970. He received the PhD degree in automation from the University of Poitiers. He is with the Laboratoire d'Automatique et d'Informatique Industrielle of Poitiers. His researchs interests are in induction motor control at low frequencies and speed observers for low speed functioning and the magnetic hysteresis modelling.

Gérard Champenois was born in France in 1957. He receive the PhD degree in 1984 and the "habilitation degree" in 1992 from the Institut National Polytechnique de Grenoble (France). Now, He his professor at the University of Poitiers (France). His major fields of interest are electrical machines associated with static converters; control, modelling and diagnosis by parameter identification techniques.