Technical article

Ferromagnetic hysteresis and magnetic field analysis

Ferromagnetic hysteresis has been a subject of research for several decades but, because of its complexity, a complete comprehension of the phenomenon and a satisfactory modeling representation is still to be reached. Besides the basic research on hysteresis developed in physical and mathematical terms, it is nowadays emerging the need for the implementation of a Hysteresis Model (HM) inside a magnetic field solution based on some numerical techniques. In fact, in many electrical devices, hysteresis comes out in complicated geometries or it is coupled to other phenomena such as eddy currents; thus a zero-dimensional HM is not always able to give sensible results.

The physical research is more linked to the explanation of the complex phenomena that lie behind the macroscopic hysteresis, like basic magnetization process, domain walls dynamics, anisotropy and thermo-dynamic aspects; for a deep understanding of this subject, a reference book can be found in [1]. On the other hand, mathematical activity tries to find out an efficient model of the phenomenon which can, in an accurate way, represent all the features of hysteretic behaviour, as in [2], [3]. Particular attention is given in these studies to the experimental activity, which is fundamental for the validation of models and often very far from an easy task, especially in the identification phase of ferromagnetic materials. Each HM needs, in fact, some particular measurements, often non-standard and difficult to perform, to fix a set of parameters characterizing the particular material under analysis.

If the work of physicists, mathematicians and experimenters is not easy, the researcher in magnetic analysis is not in front of a bed of roses. In fact, even taking for granted a HM, its coupling with a magnetic field solver is not easy. The main difficulties are tied to the choice of the most suited HM for the particular application and the insertion of this model inside an iterative nonlinear scheme that can handle polydrome characteristics. The solutions of these problems are far from univocal and an analysis of the present literature shows many approaches and several solution algorithms. This is a clear sign of an unsettled research topic where researchers are still looking for a complete and satisfactory solution. Even if the spread of procedures is vast, in the last few years some trends in HM and nonlinear algorithms seem to emerge. From the examination of the main magnetic analysis conference proceedings of the last year (INTERMAG, COMPUMAG, IGTE, etc.) some indications can be gained. Classification of the papers presented can be made according to the used model, the nonlinear technique and the application area, as they are shown in Fig. 1, 2 and 3.

As it turns out, the Preisach family is the most used, while the Fixed Point (FP) technique comes out as the preferred nonlinear solution scheme. In the following, some reasons for these preferences will be highlighted.

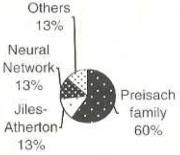


Fig. 1. Classification of presented papers concerning the models.

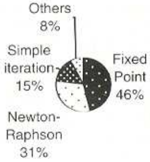


Fig. 2. Classification of presented papers concerning the nonlinear technique.

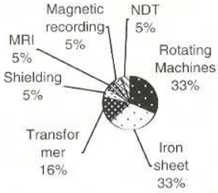


Fig. 3. Classification of presented papers concerning the application area.

Preisach family of hysteresis models

During the 30's, Preisach model has been devised to mathematically describe the main features of ferromagnetic hysteresis. From then on, its use has become widespread and several models have been generated by the basic Classical Preisach Model (CPM) to take into account peculiar characteristics of ferromagnetic hysteresis. Thus, it is quite obvious to speak about a "family" of Preisach models, all sharing the basic features of CPM.

In CPM the hysteretic behaviour is considered as a scalar phenomenon, that is magnetic field h and magnetization m are directed along the same direction. Material magnetization is described by means of a superposition of elementary relay operators, defined on the external magnetic field h and sharing the same magnetization amplitude. Each operator shows hysteresis on the output magnetization m. The up and down switching field values of these operators can be used to represent graphically the model in a plane, called the Preisach plane, like in Fig. 4.

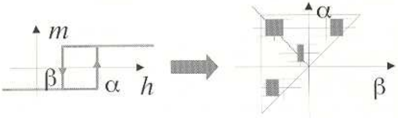


Fig. 4. Graphical representation of Preisach model.

As it is evident, every material has its own distribution of operators on the Preisach plane; for instance, a soft magnetic material has most of its operators concentrated near the coercive field, where the magnetization shows an abrupt change. The Preisach Distribution Function (PDF) describes how the operators are placed in the Preisach plane. This function has to be obtained for each material by means of measurements on specimens. As a matter of fact, several well established identification procedures have been devised and also efficient and reliable routine measurements are often available. Due to their definition, the operators have only two states corresponding to the positive and negative saturation. The history of the applied field univocally determines the state of each operator and subdivides the Preisach plane in two areas of + and – saturated operators. The interface between these two zones is a staircase line whose vertices are the turning points of the applied magnetic field. One of the main characteristics of CPM is the "wiping out" property: every trace of the applied field history is deleted by a greater subsequent input. This behaviour allows the storage of the material history only in some turning points between two extremes of the applied field.

These properties make the Preisach model an efficient tool for hysteresis handling even if it neglects some aspects of ferromagnetic behaviour.

Reversible magnetization: CPM takes into account the magnetization due to irreversible processes that occur inside the material. Besides this contribute, the reversible magnetization has to be taken into account and this can be done with operators which have null area ($\alpha=\beta$). The distribution of these operators has to be obtained by measurements on the specimen. This contribution becomes important when the material reaches saturation.

Mean field effects: the applied magnetic field is the input for CPM. However, the magnetization inside the material creates, in its turn, a magnetic field, altering the applied one. Therefore, the same value H_a of an external field creates different effects when it is applied at different magnetization levels. This effect is taken into account by changing the effective magnetic field acting on the material:

$H_p = H_a + kM$

where H_p is the effective field acting on the Preisach plane, H_a is the applied external field and k is a material dependent constant. This model is called the Moving Preisach Model (MPM) and is used to overcome the congruency property [4].

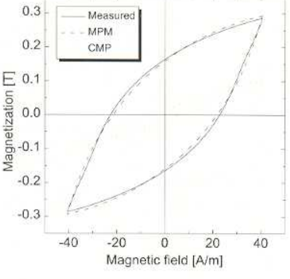


Fig. 5. Comparison of experimental and simulated hysteresis loops considering CPM and MPM.

Rate dependency: as it has been defined, CPM depends only on the magnetic field values; but often the rate dependence of the applied field on the material output is found: for instance, the so called excess losses in soft magnetic materials follow a behaviour which is frequency dependent. To take into account this fact the instantaneous switching of CPM should be substituted by a time dependent evolution. Dynamic Preisach Model (DPM) alters the nature of the relay operators, allowing them to take also intermediate values between the saturated extremes [5]. DPM allows one to take into account the rate dependency at the expenses of an easy storage of the applied field history. In fact, now the operators have a continuous evolution and so the Preisach plane is not anymore divided in two + and - areas. A "blurred" region usually separates the two saturated regions and the amplitude of this band depends on the frequency of the applied field. Some implementations of this modified Preisach model can be found in [18].

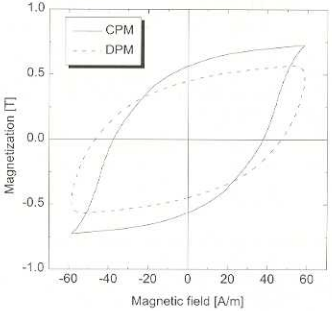


Fig. 6. Computed hysteresis loops under a given H-waveform using CPM and DPM (f=100 Hz).

Vector hysteresis: in order to overcome the scalar nature of the CPM and handle also vector hysteresis phenomena, where magnetic field and magnetization are not directed along the same direction, some further extension of CPM can be devised. The vector behaviour can be inserted in Preisach model in different ways, by considering a Vector Preisach Model (VPM) as a superposition of several CPM directed along different directions, as proposed in [2], or attributing to each elemental operator a vector nature like in [6] or [7]. This process allows treating both isotropic and anisotropic materials.

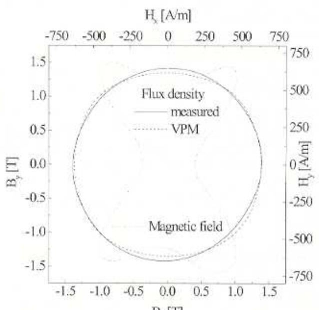


Fig. 7. Rotational hysteresis loci.

As a characteristic common to all the models belonging to the Preisach family, the input of the models is the magnetic field H, while magnetization is the output. This issue will have to be considered when coupling the model with a field solution.

Fixed Point nonlinear technique

The Fixed Point (FP) nonlinear solution method has been proposed in magnetics, several years ago by Hantila [8] and has been extensively used in nonlinear magnetic fields analysis with Finite Element Method [9]. The method can handle in a very efficient way monodrome nonlinear characteristics, imposing very little constraints on them. For instance, a rough definition of nonlinear curve and the presence of inflection points are allowed. The technique approximates the nonlinear curve by means of a fixed slope linear characteristic summed with a variable nonlinear residual which has to be evaluated through an iterative process. The main feature of FP technique is a usually slow but stable convergence to the solution point. As a matter of fact, it has quite complementary features with respect to the widespread Newton-Raphson method which has usually a fast convergence speed but which can become unstable and divergent in some particular cases [10]. Besides the treatment of nonlinear curves, the method shows the same convergence properties with hysteretic characteristics. Especially in these cases, it is possible to exploit the robustness and reliability of the method [11, 12].

Coupling of the field solver with the HM

While in the basic research on hysteresis a zero-dimensional field distribution is usually considered, in the analysis of electrical devices the spatial distribution of magnetic quantities cannot be neglected, thus a hysteretic field solution is needed. Due to the significant computational time requested by the hysteresis model, this process is usually up to now limited to one or two dimensional problems. In these cases, the most convenient field formulation is expressed in terms of the magnetic vector potential, allowing a simple solution of problems in presence of currents, both imposed and induced. Unfortunately, the vector potential solution gives as output the time behaviour of magnetic flux density that is not directly interfaced with a Preisach model which requires as input the magnetic field. A possible approach could be to change the magnetic vector potential with the magnetic scalar potential allowing a magnetic field output. However, such a field solution can be applied only to flux tubes where a magnetic potential can be defined. Another way could be the inversion of the Preisach model, using the magnetic flux density as input variable. This approach is feasible with CPM [13], but it is practically impossible with more sophisticated HM, such as DPM.

A more satisfactory solution is given by a particular use of FP scheme. In fact, FP allows an efficient interface between HM and magnetic vector potential solution by means of its *H-version* [14]. In this form, FP takes in input the flux density pattern and allows an estimate of the magnetic field, which can be given in input to the HM and used to compute the nonlinear residual. It can be shown that the before mentioned convergence properties hold also in this particular version of FP [15].

Examples of application

The field solution scheme before presented, based on a Preisach model of hysteresis coupled to a Fixed Point technique, can be applied to the study of electromagnetic field configurations. Some examples regarding both one and two dimensional computations will be presented.

1D computations

This particular field formulation can be used when the magnetic flux distribution inside a ferromagnetic lamination has to be studied. This problem, simple in appearance, needs to take into account an accurate material modeling together with the presence of macroscopic eddy currents. This study allows gaining an insight on the interactions of these phenomena in the lamination thickness when the use of the classical formulas for eddy current and hysteresis losses can give inaccurate results. The use of a numerical field solution allows the analysis of different flux supply conditions, ranging from the sinusoidal to the distorted ones produced, for instance, by electronic supply. The use of a magnetic vector potential formulation easily handles flux imposed conditions, allowing a good simulation of the experimental conditions in the Epstein frame; thus, comparisons with measurements are readily made.

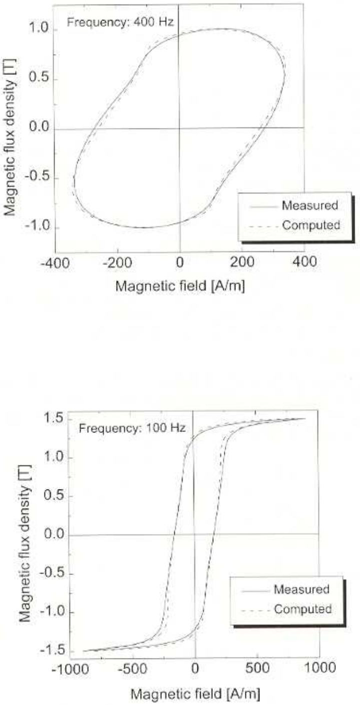


Fig. 8. Dynamic cycles of a NO FeSi alloy under sinusoidal flux condition at different magnetic flux densities and supply frequencies.

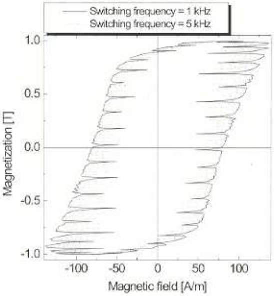
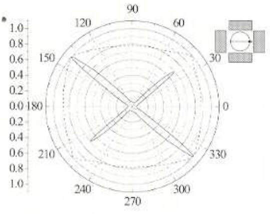


Fig. 9. Dynamic hysteresis cycles for a NO FeSi alloy under PWM supply condition for two values of the switching frequency .

2D computations

A part from some very simple geometrical and supply configurations, the analysis of two-dimensional field problems requires the use of a vector hysteresis model because seldom H and M vectors are directed along the same line. The use of the magnetic vector potential together with H-version FP makes easy the implementation of HM inside an existing field solver code. For instance, the analysis of a two axis magnetizer, used for measurements on materials, can be treated, looking at the non-uniform distribution of the magnetic flux density inside the material specimen [18, 19].

B_{max}=1.44 T H_{max}=988 A/m



B_{max}=1.46 T H_{max}=1304 A/m

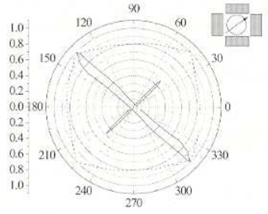


Fig. 10. Normalized hysteresis loci at the center of a material specimen (anisotropic FeSi alloy) inside a two axes magnetizer with two different directions of the material easy axis, solid line H field, dashed line B field.

Another 2D problem requires the computation of the eddy current distribution in a 2D section of the device, knowing the waveform of the supply magnetic flux flowing along the normal to the considered plane. This problem can be handled by a T-Ω formulation which enables the direct use of Preisach like models.

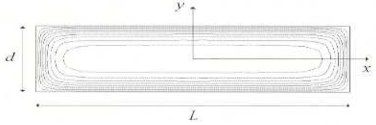


Fig. 11. Instantaneous path of the eddy currents (1 T, 400 Hz; L/d=4)

Conclusions

The solution of hysteretic field problems is becoming a state of the art computation technique. As a matter of fact, the research activity is following different roads but some common features are emerging among the possible approaches to the problem. The use of Preisach models is more and more widespread due to its efficiency and robustness. From the point of view of nonlinear solver, Fixed Point shows some advantages with respect to other nonlinear techniques as the work of many researchers seems to show. Anyway, despite the great successes achieved in these last few years, a lot of work has still to be done both on the HM and on the field solution sides. For instance, voltage driven solutions are in fact rarely found in the literature even if this is a key issue in the analysis of electrical machines.

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ENDE '99

Fifth International Workshop on Electromagnetic Nondestructive Evaluation

It gives me great pleasure to invite you to attend the Fifth International Workshop on Electromagnetic Nondestructive Evaluation (ENDE '99) being held at the Marriott Hotel in Des Moines, Iowa, U.S.A., from August 1 through August 3, 1999. The aim of the ENDE workshop is to provide a forum for discussing recent developments in the growing field of electromagnetic nondestructive evaluation. Previous ENDE workshops were held in London, U.K., Tokyo, Japan, Reggio Calabria, Italy and Paris, France.

Prospective authors are required to submit a two page long, short version of the paper, either electronically or on hard copy, no later than March 30, 1999. All papers will be evaluated and the authors will be notified regarding acceptance or rejection before April 5, 1999. Authors of papers selected for presentation will be requested to submit an eight page paper for peer review. Selected full papers will be published and distributed to conference attendees by IOS Press.

The workshop will commence on Sunday, August 1, 1999, with a reception to welcome participants and spouses. The technical sessions will commence on August 2 and last two full days. A tour of the Center for Nondestructive Evaluation and other on-campus programs in NDE at Iowa State University will be arranged for all participants on Tuesday evening. The number of papers will be limited so as to allow ample time for discussions. Both contributed and invited speakers will be featured. The workshop banquet will be held on Monday evening.

A block of rooms has been set aside for the workshop attendees at concessional rates ($99.00 + taxes for single or double occupancy per night). Reservations for hotel rooms must be received on or before July 12 to take advantage of the concessional rate.

Free transportation between the airport and the hotel will be provided by the Marriott Hotel. Additional details and registration forms are available on the workshop website (http://marg.ee.iastate.edu/ende). All correspondence relating to the workshop may be directed to:

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All of us on the Standing Committee, as well as on the Organizing Committee, look forward to your presence at the workshop. Please do not hesitate to contact me if you have any questions relating to the workshop.

Satish S. Udpa
Chairman, ENDE'99