Description of TEAM Problem: 32
A Test-Case for Validation of Magnetic Field Analysis with Vector Hysteresis

O. Bottauscio[^], M. Chiampi[*], C. Ragusa[*], L. Rege[*] and M. Repetto[*]

[^]Istituto Elettrotecnico Nazionale Galileo Ferraris, Torino, Italy .
[*]Dipartimento di Ingegneria Elettrica Industriale, Politecnico di Torino, Italy

***Abstract*-- A test case for validating 2D and 3D magnetic field analysis codes, including hysteresis, is presented. For this purpose, an experimental set-up constituted by a three limbed ferromagnetic core fitted with pick-up coils has been especially designed and built. Unidirectional or rotational flux patterns and distorted waveforms can be generated by modifying the supply conditions of the coils. Various measured local and integral output quantities, under different operating conditions, are presented for comparison with computer simulations.**

I. Introduction

Hysteresis phenomena play an important role in the definition of the working conditions in many electrical devices, influencing not only the distribution of the magnetic field, but also the waveforms of the linked electric quantities [1-3]. Thus, the use of efficient and reliable models for the prediction of the electromagnetic behavior is an important tool for the designers of the electrical apparatuses. To this aim, it is crucial the availability of experimental results to validate the theoretical models. A quite wide spectrum of data is present in literature, especially in the physical science environment, for verifying the quality of hysteresis model in very simple structures under controlled supply conditions [4]. On the contrary, there is a lack of reference data for validating the more complex computational procedures which insert the hysteresis model inside the magnetic field analysis, in order to reproduce the actual operating conditions of electrical devices.

A reference case tailored for the analysis of hysteretic cores should have the following features:

- simple geometrical structure, but including the same operating conditions as in electrical devices;
- controlled supply systems;
- magnetic cores without air-gaps to highlight the role of magnetic material behavior;
- very low supply frequency to avoid skin effects.

A structure having the above features is the eccentric torus, presented in [2], which is found to be a good test bench for scalar hysteresis. In this paper the experimental campaign is extended to rotational flux patterns by employing a three-limbed magnetic core with suitable supply conditions. The measures are finally compared with the results provided by Finite Element computations involving a vector hysteresis model.

II. General Description of the Test and Experimental Setup

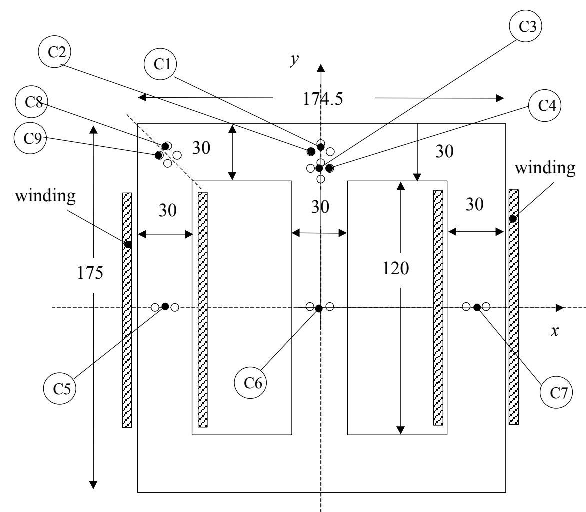

Fig. 1 Structure of the device fitted with pick-up coils (dimension in mm)

The test bench is the three-limbed ferromagnetic core, presented in Fig. 1. The core is made of five Fe-Si 3.2% wt, 0.48 mm thick laminations, having conductivity σ=1.78 MS/m and mass density δ = 7650 kg/m^3. Two windings of 90 turns are placed on the external limbs; the DC resistance of each winding is of 0.32 Ω. These windings can be both connected together or supplied by two independent controlled voltage sources driven by a power amplifier (DC-coupled CROWN 5000VZ). Pick-up coils (C1-C9) of 5 turns are displaced in different parts of the core in order to measure local magnetic flux densities (see Fig. 1). Low-noise preamplifiers (SRS SR560), having a gain of 1 to 50000 and a noise of 1.265 nV at 10 Hz, enable satisfactory accuracy for flux density values greater than 10 mT at 10 Hz.

III. Material Analysis and Modelling

A. *Material experimental data.*

The hysteretic constitutive relation between magnetic flux density and magnetic field has to be taking into account by a convenient model. Moreover, the identification procedure of the material model requires a convenient set of experimental data. For this purpose, a set of measured unidirectional symmetrical loops, obtained through the usual Epstein frame are provided. Due to spatial anisotropy, measurements in different spatial directions are necessary: for this purpose, different angular directions of application of magnetic field are obtained by shearing the ferromagnetic strips along different spatial directions with respect to the rolling direction.

The analysis is developed at a frequency of 10 Hz. At this value the signal amplitudes guarantees good accuracy of the experimental data, while the influence of skin effect is negligible, as proved by the dynamic hysteresis loops measured at different frequencies during some preliminary tests (Fig. 2).

Experimental data are available at URL http://www2.polito.it/ricerca/cadema/Team32/home.html.

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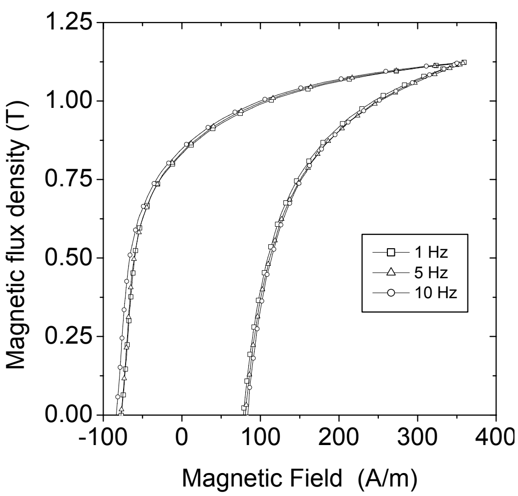

Fig. 2. Dynamical loops measured at different frequencies.

B. *Preisach model identification.*

The hysteretic constitutive relation between magnetic flux density and magnetic field can be accurately computed by taking into account the anisotropic vector Preisach model, whose details, for instance, are presented in [2]. Anyway, a simple scalar Preisach model could be used to initially explore a few aspects of the problem. In this case the identification of Preisach Distribution Function (PDF) $P_{irr}(\alpha,\beta)$ can be obtained by assuming the factorisation property $P_{irr}(\alpha,\beta)=\varphi(\alpha)\cdot\varphi(-\beta)$, justified on physical basis for a given class of magnetic material as proposed in [6]. Function φ can be obtained through different ways [7]-[8]. A simple but approximated expression for function φ is the Lorentzian one, as proposed by Bertotti in [8]:

$$\varphi(x)=\frac{C_1}{C_2\cdot C_3\sqrt{\pi\left(\frac{\pi}{2}+\tan^{-1}\left(\frac{1}{C_2}\right)\right)}}\frac{1}{1+\left(\frac{x-C_3}{C_2\cdot C_3}\right)^2}$$

Finally, the reversible part of the magnetisation can be assumed in the form [4]:

$$B_{rev}(x)=D_3\cdot x+D_1\cdot D_2\tan^{-1}\left(\frac{x}{D_2}\right)$$

Best fit values of parameters C_1, C_2, C_3 and D_1, D_2, D_3, calculated for the rolling direction, are reported in Table 1.

Table 1
Best values for the parameter of the Lorentzian function and reversible part for the rolling direction.

C_1 [$T^{-1/2}$]	C_2	C_3 [Am^{-1}]	D_1 [TmA^{-1}]	D_2 [Am^{-1}]	D_3 [TmA^{-1}]
1.17	0.79	59.78	$1.86*10^{-4}$	10	$1.29*10^{-4}$

In this way, as it is presented at URL http://www2.polito.it/ricerca/cadema/Team32/home.html, the reconstruction of magnetization loops is not accurate but, anyway, for codes which do not incorporate numerical PDF identification, the Lorentzian function may be used as a first approach for hysteresis modelling.

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The computational and experimental analysis has been developed under four different supply conditions below detailed:

- **CASE1**: windings are connected in series with an additional resistance R_s=11.1 Ω; the series is supplied by a controlled sinusoidal voltage of 13.5 V (peak value);
- **CASE2**: the same circuit of the previous point, but the controlled supply voltage includes both a first harmonic (11.8 V peak value) and a fifth harmonic (11.8 V peak value) having the same angular phase;
- **CASE3**: each winding is connected in series with a 11.1Ω resistance, one is supplied by a sinusoidal voltage (14.5 V peak value), the other is supplied by a co sinusoidal voltage (14.5 V peak value);
- **CASE4**: one winding, the left one, acting as primary, is series connected with a 11.1 Ω resistance and is supplied by a sinusoidal voltage (10.9 V peak value), while the other one, acting as secondary, is connected to a load resistance of 0.05 Ω.

A. *Simulation results*

Although the proposed problem has a short axial length (z-direction) and would be better suited to 3D field analysis codes, a 2D representation could be used to initially explore a few aspects of the problem. Then, the following simulations are performed by a 2D voltage driven field formulation having as unknowns the nodal values of magnetic vector potential. For codes which do not incorporate external circuit connection, the current waveforms can be directly used as the input. The hysteretic constitutive relation between magnetic flux density and magnetic field is taken into account by the anisotropic vector Preisach model, whose details are presented in [2]. The non linear problem is linearized by means of the Fixed Point technique, giving rise to an iterative procedure. Under periodic supply conditions, the linearized problem is developed in the frequency domain through a truncated Fourier series, following the approach detailed in [2].

In **CASE1** only unidirectional flux patterns are generated. Fig. 3 and 4 compare the experimental and computed flux densities in the central and left limbs respectively. While satisfactory agreement is found in the central leg, a lack of accuracy is present in the other limb. Such a discrepancy can be attributed to a significant leakage flux, whose path flows around the winding in the third dimension, the structure is in fact only 2.5 mm thick versus a cross section dimension of about 170 mm. Anyway, the flux in the third dimension is approximately connected in parallel with the one inside the lamination which obeys a 2D distribution. Thus, outside the supplied leg the agreement between simulations and measurements is satisfactory, as for instance in pick-up coil C6 of Fig. 3. The three-dimensional behavior could be included in the computation by adding a leakage inductance in the electric circuit, but in any case the local values of magnetic flux density cannot be corrected. Satisfactory agreement is also found as regards the waveform of the supply current, as reported in Fig. 5.

Similar considerations can be repeated for **CASE2** both for flux density (Fig. 6) and for supply current (Fig. 7), which shows a significant fifth order harmonic. The presence of this component gives rise to minor loops in the local hysteresis cycle, as shown by Fig. 8 which presents the results computed in a point of central limb corresponding to coil C6. It must be remarked that hysteresis loops can only be computed since the structure is not fitted with coils for measurement of magnetic field vaues.

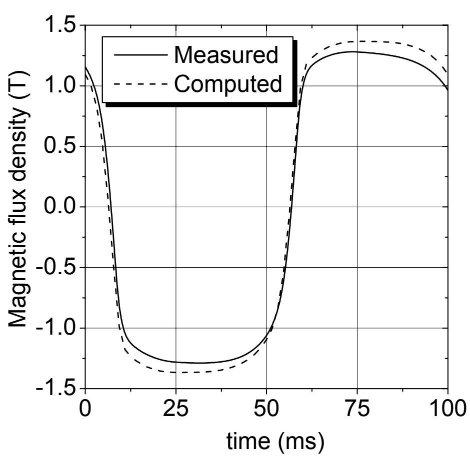

Fig. 3. CASE1: computed and measured waveform of magnetic flux density in the central limb (coil C6).

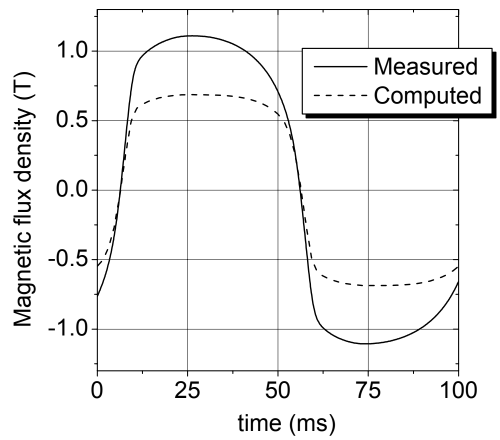

Fig. 4. CASE1: computed and measured waveform of magnetic flux density in the left limb (coil C5).

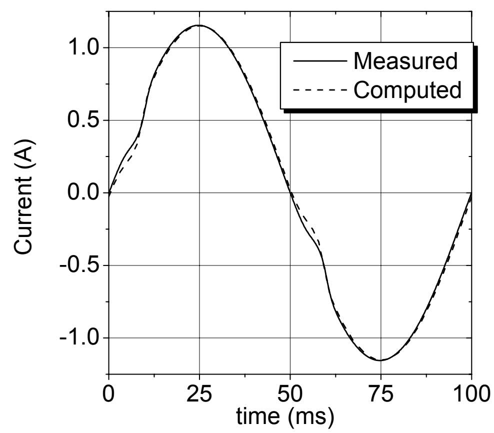

Fig. 5. CASE1 Computed and measured waveforms of the current.

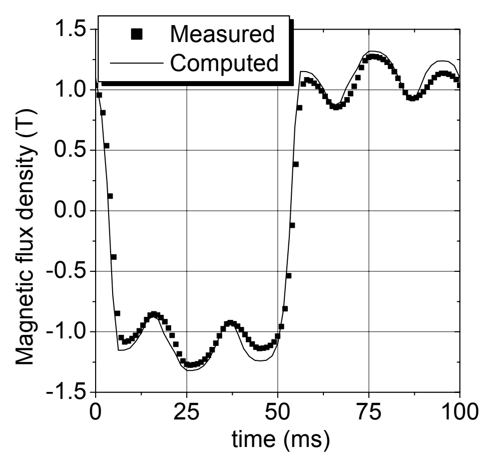

Fig. 6. CASE2: Computed and measured waveform of magnetic flux density in the central limb (coil C6).

In **CASE3,** significant rotational effects are produced, in particular in the regions of pick-up coils C1-C2 and C3-C4. The computational model is found to be able to reproduce with sufficient accuracy the flux distribution in the core as shown in Fig. 9, presenting the locus of magnetic flux density obtained by combining experimental values of pick-up coils C3 and C4. The waveform of computed and measured supply currents in the two windings are compared in Fig. 10.

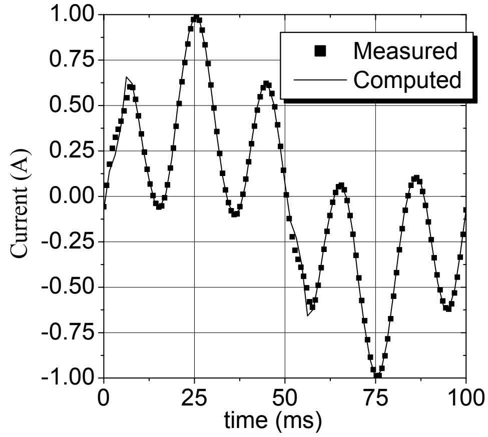

Fig. 7. CASE2: Computed and measured waveforms of the current.

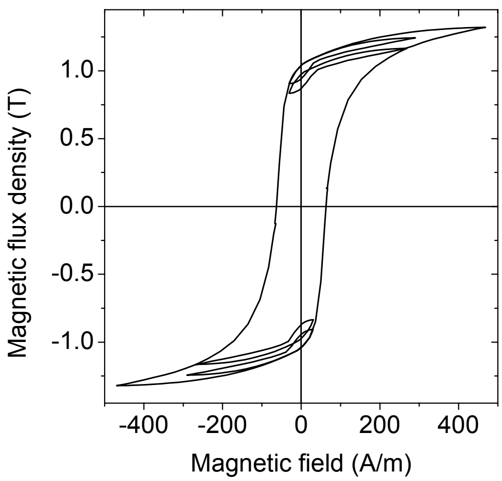

Fig. 8. CASE2: computed hysteresis loop in point C6.

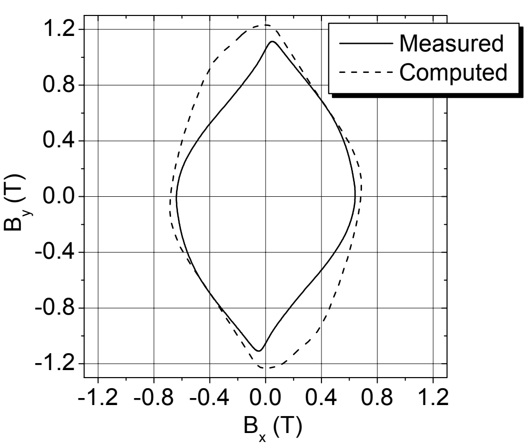

Fig. 9. CASE3: computed and measured B-loci (coils C3 and C4)

In **CASE4**, the effect of the primary and secondary magneto-motive forces can be highlighted. In Fig. 11 both experimental and simulated current waveforms are shown and it can be seen that there is a phase shift between them. Fig. 12 shows the local magnetic flux density on pick-up coils C6 (central leg) and C7 (leg under secondary winding).

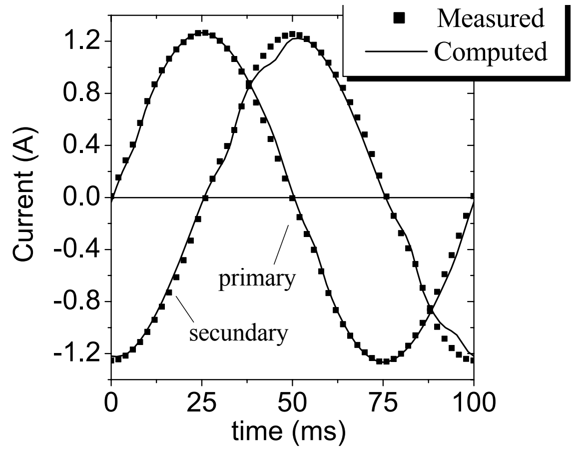

Fig. 10. CASE3: Computed and measured waveforms of the current.

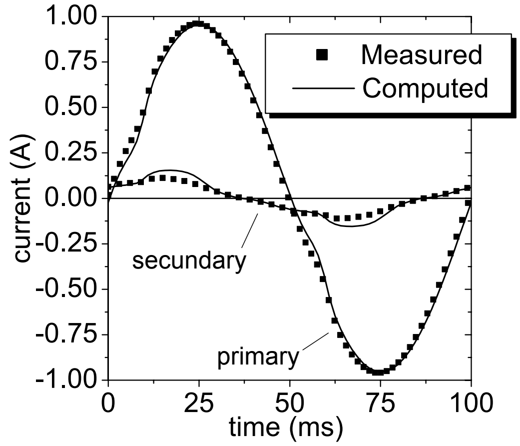

Fig. 11. CASE4: Computed and measured waveforms of the current

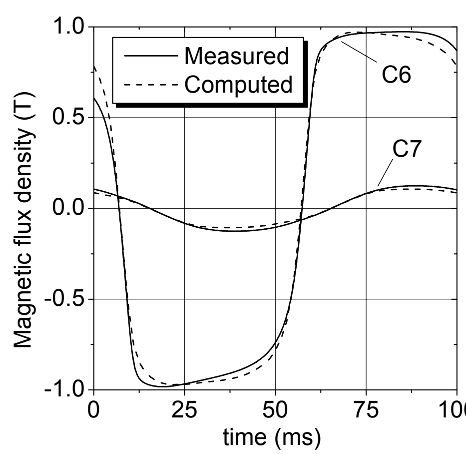

Fig. 12. CASE4: Computed and measured waveforms of magnetic flux density in the left and right limbs (coil C6 and C7)

V. DOWNLOAD OF PROBLEM DATA

All data presented in this document can be accessed in the web site:

http://www.cadema.polito.it/team32/home.html

The site is structured in 4 separate sections:

- introductory section: contains some information about the motivations of the work;
- geometry section: contains drawing of the magnetic core, data on the windings and tables of pick-up coils coordinates;
- material section: gives access to the material data and allows to download the hysteresis loops measured on the Epstein frame along the 4 directions of shearing. For each direction a file containing the H, B couples of several symmetric hysteresis loops is present and can be downloaded. In addition, for researchers which do not have access to an identification procedure, a simplified expression of the Preisach Distribution Function for the rolling direction material is reported;
- measurement data section: contains the data files of the measured results of the 4 cases above described with the values of the circuit components. For each case the following quantities can be downloaded: waveform of supply voltages, waveform of currents, waveforms of magnetic flux density acquired on some pick-up coil.

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