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## Modeling of a Non-Linear Conductive Magnetic Circuit Part 2 : Bond Graph Formulation.

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**Abstract**—We have presented in "Modelling of a non-linear conductive magnetic circuit - Part 1 : Definition and experimental validation of an equivalent problem" a non-linear dynamic model in the case of simple shaped magnetic circuit. In order to describe easily coupled electric-magnetic-mechanic problems, a general method using Bond Graph techniques is proposed. The method, tested in the case of electrical coupling, has been implemented in the P.A.C.T.E simulator. The experiment gives results in accordance with the simulated ones.

### I. INTRODUCTION

Magnetic circuits are generally used in multidomain systems where non linear and dynamical effects are of first importance. For example, the magnetic circuit of a transformer is often coupled with a secondary power electrical circuit including both multiple windings and semiconductor devices used in high signal conditions. Thus, simulated industrial problems often need to use both non linear dynamic models of components (electronic or magnetic) and a method which enables easily the generation of the equation system.

In Part 1, we have presented a magnetic model in the case of simple shaped circuits. Moreover, we were obliged to solve electrical coupled problems without electrical circuit simulator facilities.

Broadly speaking, Bond Graph (B.G.) techniques [1], [2], principally used in Automatics, are a generalisation of the Kirchhoff networks. Based on energy considerations with a single graphical formulation whatever the physical domain, B.G. enables easily to take into account coupling effects between physical domains (electrical, magnetical, mechanical).

This paper presents the implementation of the non linear magnetic model with B.G. and an experimental validation in the case of electrical coupling.

### II. MODELLING TECHNIQUE

A physical system B.G. shows how the energy flows between its different parts. The energy flow can be of any kind (electrical, magnetical, mechanical ...) but it is always characterized by the value of a power that is the product of a flow variable into an effort variable.

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TABLE I

Physical domain	Flow variable $f(t)$	Effort variable $e(t)$
Electrical	current (A)	voltage (V)
Magnetical	Flux rate (V)	Magnetomotive force (A)
Mechanical translation	Velocity (m/s)	Force (N)
Mechanical rotation	Angular velocity (rad/s)	Torque (N.m)

Table 1. Shows the flow variable and the effort variable within the domain of physics.

B.G. formalism includes basic components and macrosystems which dissipate or store energy or change the energy form.

To take advantage of this unified formalism, we have considered the state space magnetic model described in Part 1 as a non-linear magnetic core B.G. representation. The magnetic core is characterized by its length, its cross-section and by its non-linear magnetic characteristic  $B(H)$ . The magnetic flux is assumed to be the same in the core cross-section. The modelling coupling principle is given in Fig. 1. The magnetic core model can receive, store (and dissipate) any kind of energy, and it finally releases the remaining part to the rest of the system.

As an example, we consider the B.G. representation (Fig. 3) of the fault detector shown in Fig. 2. Lines with an half arrow are called "bond" and represent the energy flows and their direction. In electrical domain, the power is the product of the current into the voltage and within magnetic domain, the power is product of the magnetomotive force into the time magnetic flux rate of change. The "1" and the "0" represent power conserving elements, called respectively 1-junction and 0-junction, which transfer the energy flow from components to others. For example, in the electric case 1-junction denotes a serie connexion and 0-junction a parallel one. The "GY" gyrator, [3], is also a power conserving element which changes the energy form. In this case, electrical energy is changed into a magnetical one or vice versa. The constitutive laws of the GY girator connected to the electrical energy source, in this case of electrical/magnetical coupling, are  $u_1 = N_1.d\Phi/dt$  which is just the Faraday's law applied to the coil of  $N_1$  turns and  $M_1 = N_1.i_1$  which is the magnetomotive force definition.

Energy flows from electrical source and is stored and dissipated at first in the magnetic circuit represented by our model and secondly in the secondary electrical circuit.

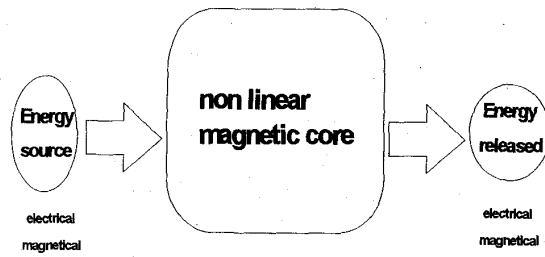


Fig. 1. Modelling coupling principle

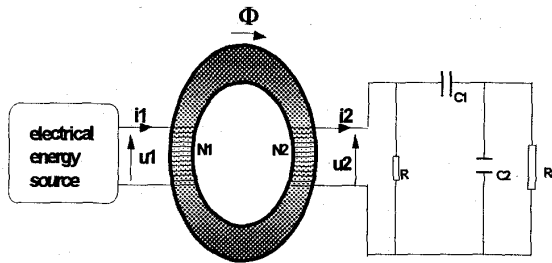


Fig. 2. Fault detector

Moreover, in B.G. formalism, each energy storage is described by a state space model. This method allows a fast and methodical acquisition of the state equations of the system and decreases the number of numeric problems which can occur in the case of non-linear systems [4].

III. RESULTS AND DISCUSSION

The choice of a simulation tool adapted to our method depends on two conditions :

Firstly to allow a B.G. formulation, secondly to be able to represent electrical circuits. The first condition is well performed by tools such as A.C.S.L. or T.U.T.S.I.M. The second one is performed by electrical simulators such as S.P.I.C.E. or S.A.B.E.R. The simulator PACTE [5]-[7], soon to be commercialized by A.N.A.C.A.D. fits with these two requirements : This simulator which includes a B.G. formulation with automatic equation generation and power electronic component models, enables the following comparison between simulation and experimental results :

- Fig. 5 shows the secondary circuit voltage and the  $\Phi(i_1)$  curve for a 50 Hz sine excitation current of the simple transformer circuit of Fig. 4. The non-sine form of the secondary voltage  $U_2$  is well represented because of the accuracy of the dynamic cycle simulation.

- Fig. 6 shows that we obtain, for the fault detector circuit of Fig. 2, the same results as in part 1, but without writing equations.

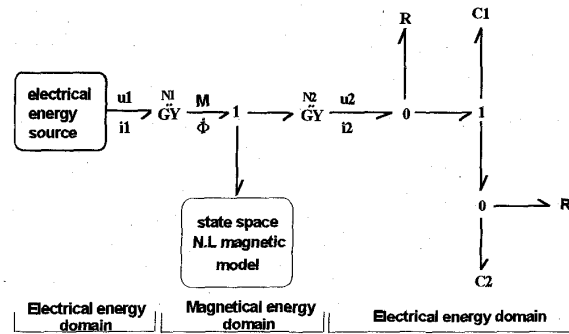


Fig. 3. B.G. of the fault detector

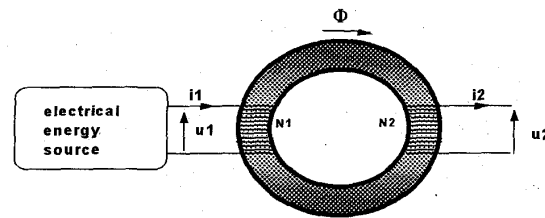


Fig. 4. Simple shaped transformer.

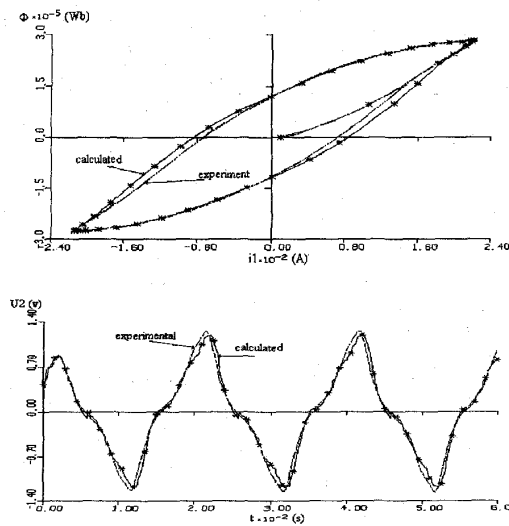


Fig. 5.  $U_2$  voltage and 50 Hz dynamic cycle for the simple shaped transformer

- Fig. 8 shows the results obtained with the fault detector of Fig. 7 for a 200 Hz current excitation.

The whole system transient behaviour is both dependant of the magnetic circuit and of the electronic components. We can notice, in this case, that the determination of the  $\Phi(I)$  dynamic characteristic allows an accurate prediction of the  $C_2$  capacitor voltage.

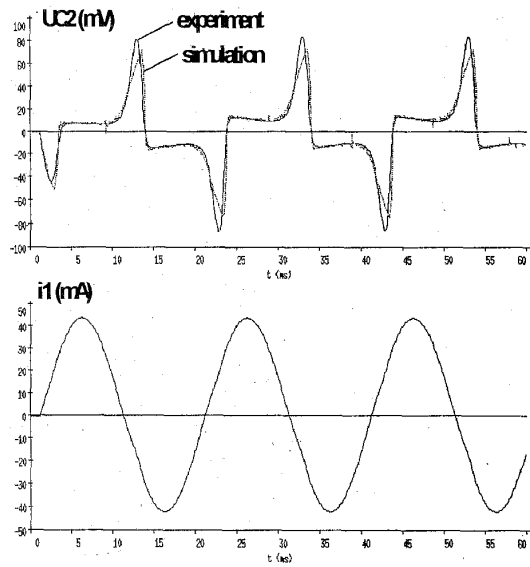


Fig. 6. Uc2 voltage and excitation for the fault detector of Fig. 2.

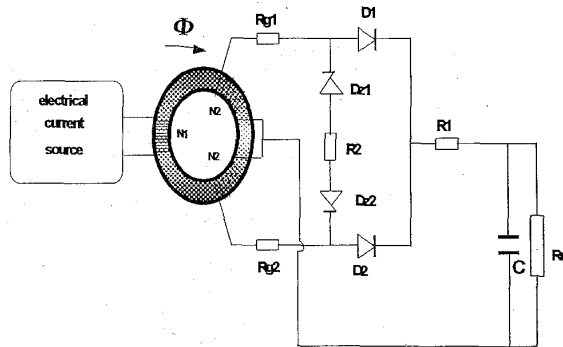


Fig 7 : More elaborated fault detector

IV. CONCLUSION

Starting from the non-linear magnetic model presented in Part I, we have used B.G. formalism to take into account coupling problems easily. The method used is general and has been integrated in a simulator dedicated to power electronics and illustrated in the case of electrical coupling.

Moreover, this formulation allows to solve non linear dynamic magnetic problems with the use of B.G. techniques as wanted by Karnopp [1].

This formulation will allow a lumped parameter elements approach to described more complex shaped magnetic circuits and electrical machines.

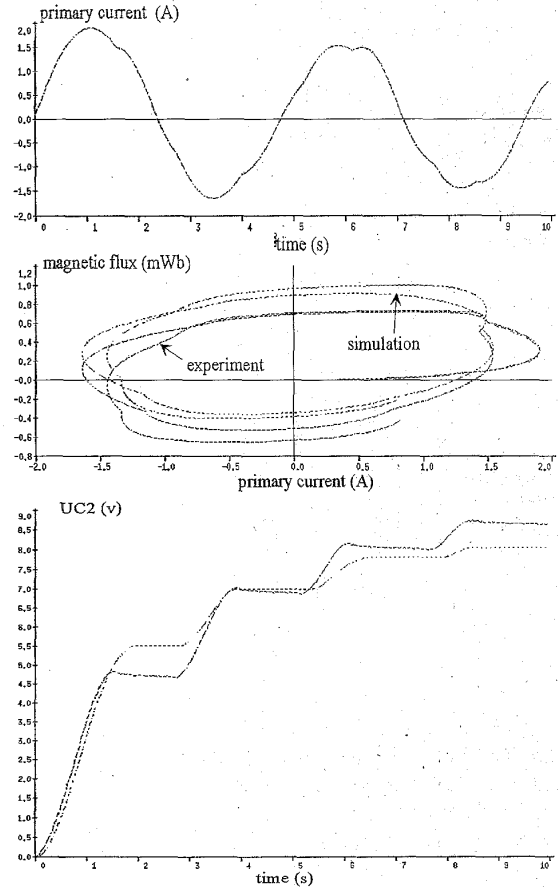


Fig. 8. 200 Hz sine excitation, capacitor voltage and dynamic characteristic for the fault detector circuit of Fig. 7.

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