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# Modeling of a current sensor with a FE-tuned MEC: Parameters identification protocol

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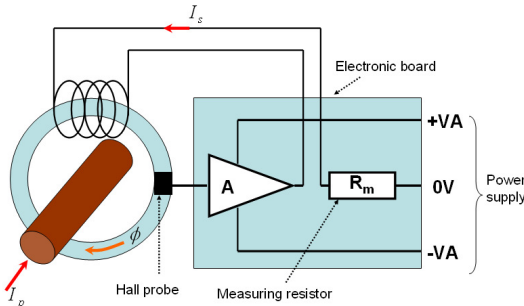
**Abstract** — This paper presents a magnetic circuit modeling of closed loop Hall-effect current sensors based on a magnetic equivalent circuit which could be simulated with a circuit type simulator software (PSPICE model). First, the principle of measurement of the closed loop Hall-effect current sensors is presented, Then, the magnetic equivalent circuit (MEC) modeling justified by the engineers' model needs is elaborated. Finally the parameters identification protocol based on 3D Finite-Elements (FE) simulations and simplex optimization method is explained.

## I. INTRODUCTION

The closed loop Hall-effect current sensors [1] can measure all kinds of current from DC to several tens of kHz with a galvanic insulation between the primary current and the measuring signal. The current sensor must have a measuring signal directly proportional to the current to be measured. In order to improve current sensors accuracy, frequency bandwidth or magnetic immunity, engineers require specific models able to reproduce signals with a good accuracy in a short time in order to test many improvement ideas. A specific model which can be implemented in circuit-type simulator software has been created in order to help engineers to improve the sensors performances.

## II. PRINCIPLE OF MEASUREMENT

The current sensor main parts are represented in Fig. 1.



**Fig. 1 : Current sensor main parts**

The primary current ( $I_p$ ) passing through the sensor creates a magnetic flux  $\phi$ . This magnetic flux is concentrated by the magnetic core. The Hall probe placed inside the air-gap of the core provides a voltage proportional to the magnetic flux density. The electronic board converts this voltage into a secondary current. This secondary current is then, at any time,

proportional to the primary current following (1), ( $N_p, N_s$ : primary and secondary coil number of turns respectively):

$$N_p I_p = N_s I_s \quad (1)$$

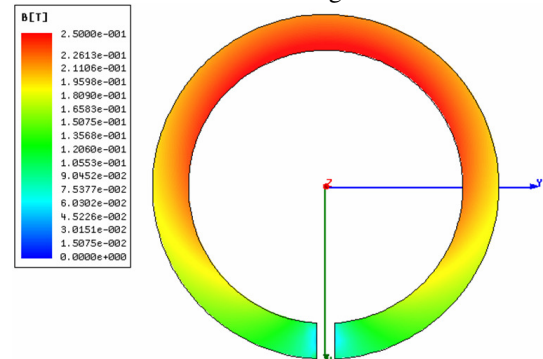
## III. MAGNETIC CIRCUIT MODELING

### A. Engineers' needs

The electronic board, necessary to create the secondary current proportional to the primary one, contains many electronic components (diodes, resistors, capacitors...). In order to test the whole system (magnetic circuit and electronic board), engineers need a model of the magnetic circuit able to be implemented in a circuit-type simulator software. The magnetic behavior non-linearities (hysteresis and dynamic effects) excludes a linear electric equivalent model (R,L,C model). A magnetic equivalent circuit or reluctance network model offers a good compromise between accuracy and rapidity. The final model must take into account all the phenomena (geometric effects, hysteresis, dynamic effects) that can create signal distortion. These different phenomena occurred by the magnetic circuit can be studied separately.

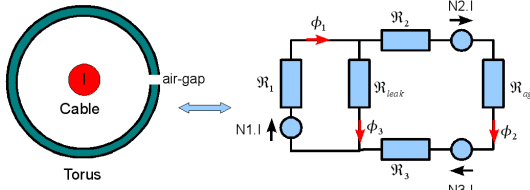
### B. Modeling of "geometric effects"

The air-gap, where the hall probe is placed, induces flux leakages which lead to local saturation of the magnetic circuit. The Fig. 2 shows the results of a 3D finite elements simulation in magnetostatic. It can be seen that the modulus flux density  $B$  inside the magnetic circuit is greatly inhomogeneous. This means that there are a lot of flux leakages.



**Fig. 2: Flux density modulus inside the magnetic circuit.**

The model must take into account these flux leakages, so the magnetic circuit is decomposed into several flux tubes like shown on Fig. 3



**Fig. 3: Magnetic equivalent circuit scheme**

With:

- $\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3$ : magnetic circuit flux tubes
- $\mathcal{R}_{leak}$ : leakage flux tube
- $\mathcal{R}_{ag}$ : air-gap flux tube
- $N1.I, N2.I, N3.I$ : fictitious magnetomotive force sources
- $\phi_1, \phi_2, \phi_3$ : magnetic fluxes.

After analysis, and in order to represent accurately the geometric effects (flux leakages, air-gap), three specific parameters that can not be identified analytically have to be determined. These three parameters are:  $\alpha$ , the angular position of the leakage flux tube,  $S_{ag}$  the cross-section of the air-gap flux tube,  $S_{leak}$ , the cross-section of the leakage flux tube.

In order to identify these parameters, an optimization algorithm [2] based on the simplex method is used. The criterion used here is the mean quadratic error between the flux density modulus calculated by a 3D FE simulation in magneto static and the flux density modulus calculated by the magnetic equivalent circuit along the mean length of a half of the magnetic circuit. In order to find constant parameters and make a compromise between linear and saturated behavior, two objective functions ( $OF_1, OF_2$ ) are evaluated. Then, these two objective functions are used to make a single objective function  $OF$  so as to:

$$OF = \sqrt{(OF_1)^2 + (OF_2)^2} \quad (2)$$

$OF$  is the simplex optimization algorithm criterion to minimize. Results of the optimization are shown on Fig. 4.

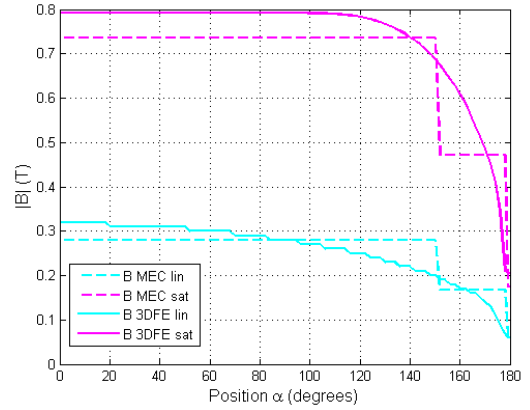
### C. Magnetic material dynamic effects modeling

The magnetic material dynamic effects are represented with a differential equation. This model is based on (3).

$$H_{app} - H_{stat}(B) = \gamma \frac{dB}{dt} \quad (3)$$

$H_{app}$  is the applied excitation field,  $H_{stat}(B)$  represents a fictitious static excitation field for a given flux density  $B$  and  $\gamma$  is a constant coefficient that represents the whole dynamic effects (eddy currents, wall motion). Assumption, limits and rules of use are described in [3]. This model can

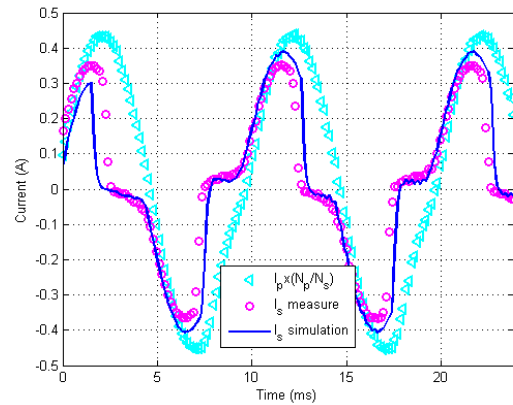
easily be introduced in the MEC seen before.  $\gamma$  is determined by comparing simulated and measured hysteresis loops.



**Fig. 4: flux density modulus versus position angle for a half magnetic circuit and air-gap. (MEC: Magnetic equivalent circuit, 3DFE: 3 dimensions finite elements, lin: linear, sat: saturated)**

## IV. RESULTS

After identification of all the parameters, the model is tested without the electronic card (the measuring resistor is directly linked to the secondary coil) for different current amplitudes and frequencies. Fig.5 shows an example for a current of amplitude 800A and frequency 100Hz. The measured primary current is imposed to the simulation, and the measured and simulated secondary currents are in good agreement.



**Fig. 5: imposed primary current and secondary current**

## V. CONCLUSION

In the extended paper, more details about the parameters identification protocol will be given. The present protocol will be applied for different magnetic circuit sizes and different materials.

## VI. REFERENCES

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- [3] Raulet M.-A. et al., *COMPEL Int J for Computation and Maths in Electrical and Electronic Eng* 27, 1 (2008) 256-265.