Evaluation of errors associated with crosstalk magnetic fields using Finite Element Method in high electrical current measurement.

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1. Introduction

In many industrial measuring applications, e.g. generated power from a wind turbine, the current carrying conductors are placed very close from each other and so the current transducer. Error in the measurement can arise due to crosstalk magnetic fields in the cores of the transducers. These errors will be increased when the windings or sensors are not uniformly distributed. These effects attached to very close current lines are undoubtedly significant when using magnetic sensors arrays [1], [2]. In this paper, a simplified bus bar current structure will be studied and simulated results will be compared with laboratory measurements. Numerical simulations are used to predict errors in two bus bar arrangements and some design guidelines are suggested to reduce the sources of errors.

Using the facilities of Electric Metrology Laboratory (LME), accredited by the European Cooperation for Accreditation (EA), experimental measurements of magnetic fields will be performed. These measurements shall be compared with values numerically calculated with the modelization by Finite Element Method. Simulations have been developed using the commercial software OPERA-3D of Vector Fields.

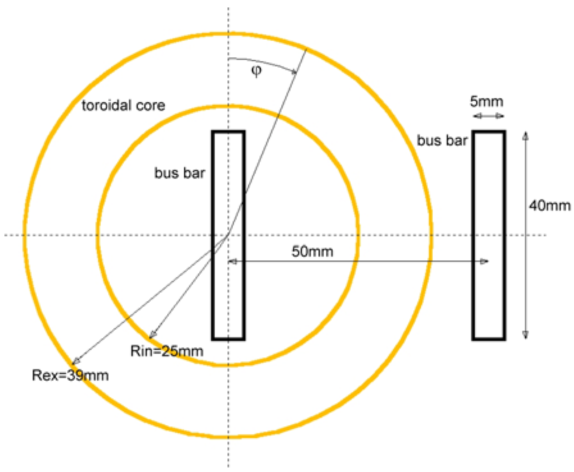

Figure 1. *Illustration of the experimental model.*

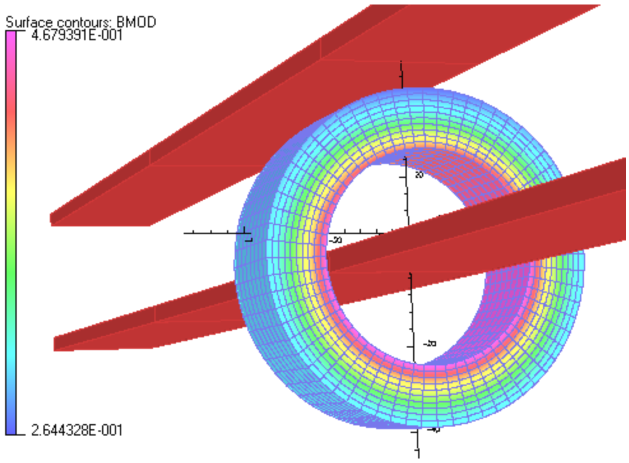

Figure 2. *Single circuit model with two conductors and the measuring torus.*

2. Results

The model consists, see figure 1 and 2, on a single circuit with current flowing through two rectangular section conductor (5 x 40 mm). One of the bars is placed in the centre of the measuring toroidal core. The parallel conductor (return bar) has the same geometry and the perpendicular distance between bars is 50mm. The geometrical characteristic of the core are the following: inner and outer radius $R_{in} = 25$mm, $R_{ex} = 39$mm and height h = 25mm. The core used is a commercial non-linear iron powder toroidal core (yellow-white) ref. T300-26D of Micrometal Inc. Magnetic flux through a magnetic torus cross-sections was chosen as the result from the numerical calculations as the response of a current transducer based on the induced electromotive force.

In this system we have done several simulations and as well the experimental measurements. The electrical parameters, as the current carried by the rectangular conductors, has been modified in the different tests, maintaining constant the permeability of the sensor element and the geometric parameters of the model.

From the Ampere's law, we can establish a correspondence between the current going through a circular toroidal core and the magnetic flux in the section of this core (because of the rotational symmetry). So we can consider our system as ideal constituted by a straight cable of depreciable section and situated in the centre of the toroidal core. A change in the symmetry will produce a change in the magnetic flux in the different sections of the core [3], [4].

The figure 3 shows the magnetic flux, obtained by simulation for the different sections of the toroidal core in the case of a sole bus bar in the inner and the complete system constituted by two bus bars, one in the inner and the other one outside and currying the same current in the same sense. Both graphics are compared with the value of the magnetic flux obtained in the ideal model. In the three cases shown, the current currying by each conductor is I = 300A and the relative permeability of the core is μ = 213.

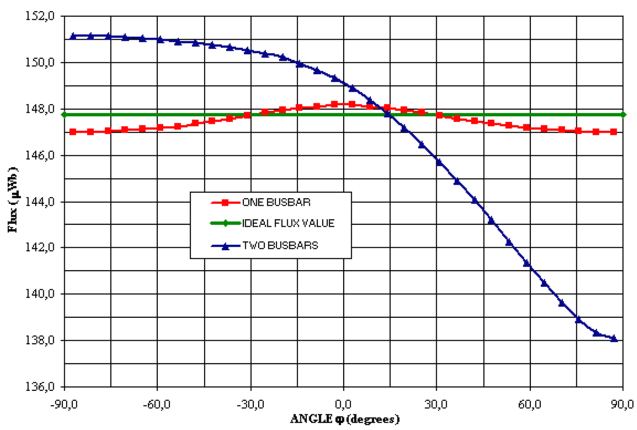

Figure 3. *Graphics for magnetic flux measured with one and two busbars, versus the angle of the sensor.*

The ideal magnetic flux corresponds to the one obtained theoretically for an infinite straight cable and for the data of our problem gives a value of 147,8μWb. In the other side, the magnetic flux due to the bus bar varies between 147,0μWb and 148,2μWb. It corresponds to a maximal deviation of 0,54% with respect to the ideal.

In the case of the two parallel bus bars, the magnetic flux shows a greater variation, due to the crosstalk, the influence of the external conductor in the magnetic material of the sensor. It varies between 138,02μWb and 151,07μWb. It corresponds to a maximal deviation 6,6% with respect to the ideal model.

As can be appreciated, the error produced by the cross-talk is predominant. The difference between both curves permit us to isolate this effect and shows a point where the value is zero (intersection point between the curves of the two bus bars). This point is situated in φ = +9,8º, see figure 3. This point is very interesting for the position of a sensor in the core, so in that position the sensor will be immune to the crosstalk effect. The asymmetry of the rectangular bus bar produces a slight variation between the magnetic flux measured in this point and the ideal.

Once considered the existence of this optimal point for positioning the sensor, avoiding of this manner the cross-talk influence, we have analysed their stability with respect to the value of the currents in the conductors in the model in study.

In this way and in a first approximation, we have studied the degree of immunity of this point with respect to variations of current by the external currents I_{CEX}, maintaining constant the current circulating by the internal conductor I_{CIN} = 300A, as shown in the figure 4. As it was imaginable, the influence of the crosstalk increases when increases the value of the current by the external conductor I_{CEX}, the stability of the point can be appreciated in φ = +9,8º where the error of the magnetic flux with respect to the internal conductor will be null.

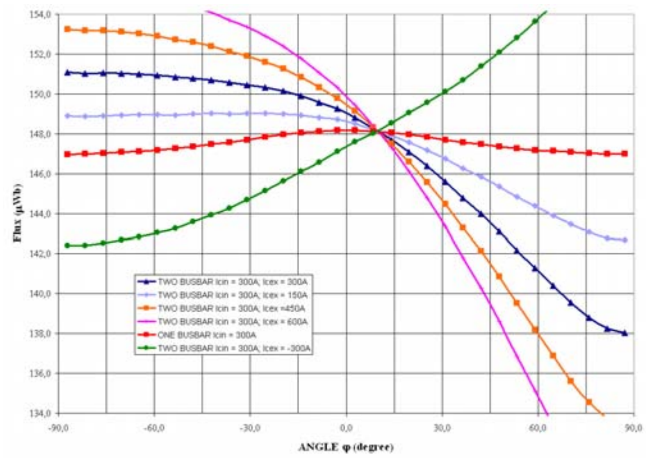

Figure 4. *Magnetic flux vs. sensor position in the core for several intensity values in the external busbar and the internal current fixed to I_{CIN} = 300A.*

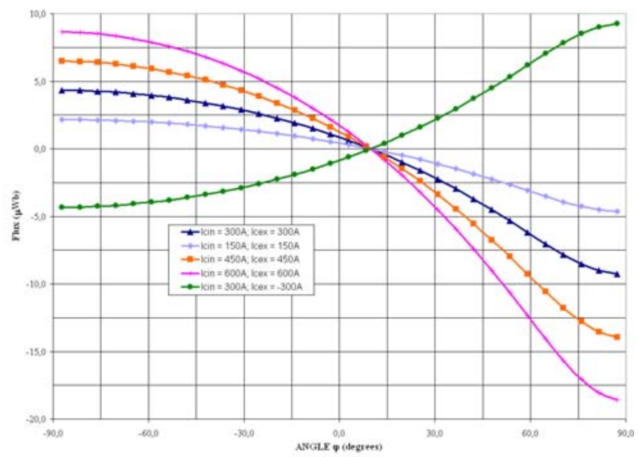

Figure 5. *Magnetic flux (crosstalk effect) vs. sensor angular position in the core for several intensity values (I_{CIN} = I_{CEX}).*

In a second part of our work we have studied the influence, in the point where we will situate the sensor, of the current going through the internal conductor. For that we have connected the internal and external conductors to the same value of current I_{CIN} = I_{CEX} and the effect of the crosstalk was analysed (difference between the flux produced by the two bus bars and the originated only for the internal conductor) with respect to the angular position of the sensor. In this analysis different values of the current were analysed for verify his effect in the influence of the crosstalk, as shown in the figure 5.

Again we can see in the figure 5 that the point situated in the angular position $\varphi = +9{,}8^{o}$ -point where the curves crossing- is independent of the crosstalk. In this way, a sensor situated in this angular position will reflect accurately the value of the magnetic flux generated by the internal rectangular bus bar no matter the value of the current circulating by the external conductor (null crosstalk)

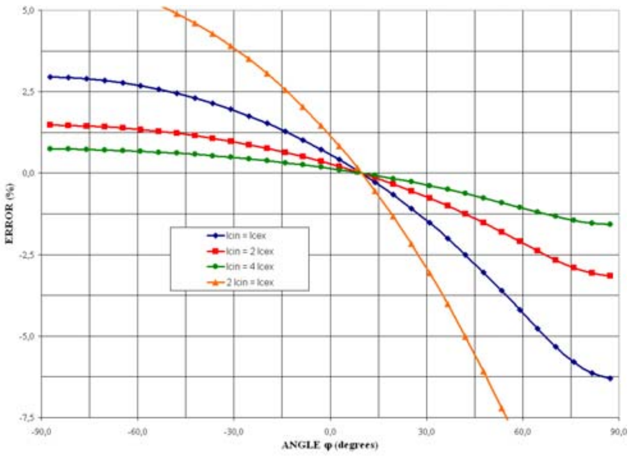

Figure 6. *Flux Error (crosstalk effect) vs. sensor position in the core for several relation between the external busbar and the internal current.*

The figure 6 shows the error produced in the magnetic flux (influence of the crosstalk) with respect to the angular position of the sensor and in function of the ratio of the currents carrying by the conductors I_{CIN} / I_{CEX}. In all analysed cases, the geometry of the model studied was constant, as well the permeability of the magnetic material of the core $\mu = 213$.

For a ratio of currents equal to $I_{CIN} = 2\times I_{CEX}$ and considering a maximum error of $\Delta\varepsilon = \pm 0{,}5\%$ the position of the sensor can be between the angles $-8{,}15^{o} \leq \varphi \leq +24{,}20^{o}$ ($\Delta\varphi_{MAX} = 32{,}25^{o}$). In the contrary if the ratio is $2\times I_{CIN} = I_{CEX}$, and considering the same maximal error of $\Delta\varepsilon = \pm 0{,}5\%$, the angular position for the sensor diminish to $+5{,}64^{o} \leq \varphi \leq +13{,}65^{o}$ ($\Delta\varphi_{MAX} = 8{,}01^{o}$). In the last case is observed that the influence of the external conductor produces a maximal deviation of 12,90% in the measurement with respect to the ideal model.

Until now, we have maintained constant the magnetic permeability of the core, but in the real case, the permeability changes in function of the current (and the magnetic flux), producing a slight displacement of the point of our interest [5].

For estimating the influence of the magnetic permeability in the stability of this point (immune point) a second model of analysis was developed. It allowed to correct the perturbation of the own material in the system (hysteresis cycle). In this way the magnetic nucleus has been substituted by another one made in metacrilate, (where the permeability is very close to the vacuum $\mu_O = 1{,}256\times 10^{-6}$ H/m) with the same dimensions of the previous one and the same geometry of the conductors carrying the current.

As could be expected after modification of the properties of the material, the immune point to the crosstalk error moves its position in a clear dependence of the magnetic properties of the material. As can be seen in the figure 7 the new position of the point has moved to the right, being now in the angular position $\varphi = +36{,}25^{o}$,

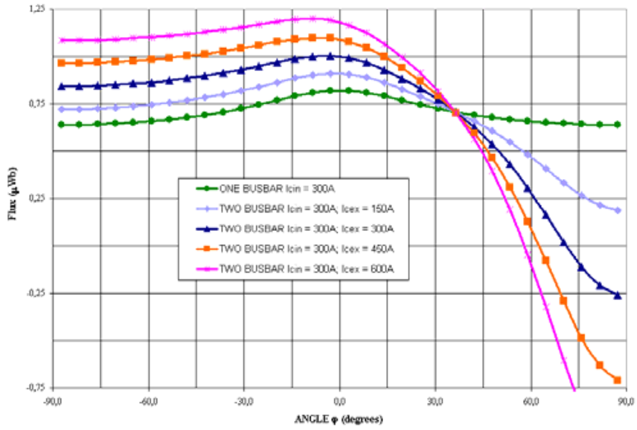

Figure 7. *Magnetic flux vs. sensor position in the core for several intensity values in the external busbar and the internal current fixed to I_{CIN} = 300A, $\mu = \mu_O$.*

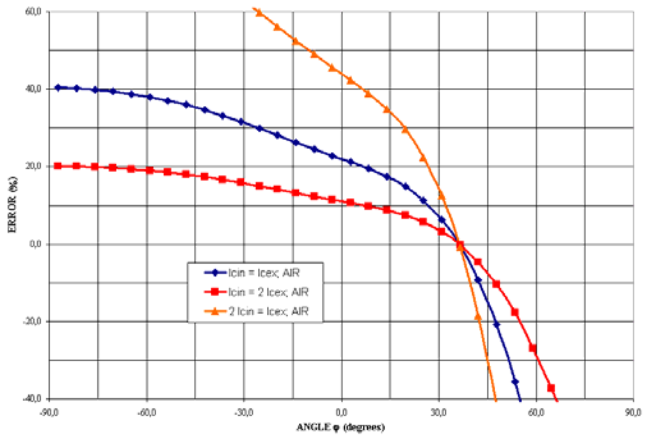

Figure 8. *Flux Error (crosstalk effect) vs. sensor position in the core for several relation between the external busbar and the internal current, material permeability $\mu = \mu_O$.*

In this situation the ideal magnetic flux, calculated theoretically in the section of the torus is 0,67µWb . A comparison of this value with the value generated only by the internal conductor gives a maximal deviation of

21,50% with respect to the ideal flux, so an important variation, due to the geometry of the conductor.

The figure 8 represents the error introduced in the magnetic flux due to the crosstalk with respect to the angular position of the sensor and in function of the ratio between the currents carrying by the internal and external conductors I_{CIN} / I_{CEX} in the nucleus of permeability μ_O. As it can be seen a diminution of the permeability produces an increase of the estimated error.

As a practical situation, taking a maximum admissible error of $\Delta\varepsilon = \pm 0,5\%$ in the measurement and supposing a ratio of currents of $I_{CIN} = 2\times I_{CEX}$; the angular position of the sensor could be between the angles $+35,40^o \leq \varphi \leq +36,95^o$ ($\Delta\varphi_{MAX} = 1,55^o$).But if the current currying by the external conductor is $2\times I_{CIN} = I_{CEX}$, the angular position for maintaining the level of error is reduced to $+36,16^o \leq \varphi \leq +36,48^o$ ($\Delta\varphi_{MAX} = 0,31^o$).

Comparing the errors obtained in the magnetic flux in the studied cases (permeability of the material $\mu = 213\mu_O$ and $\mu = \mu_O$ as shown in figures 6 and 8, can be deduced that the nucleus of metacrilate is much more sensible to the angular position, so the position of the sensor must be very accurate. This can be seen in the high slope of the curves close to the immune point.

In this situation it could be possible that the dimensions of the used sensor were higher than the maximum allowed angle for a given limit of error, so the error always be higher than previously fixed in the measurement of the current.

Our modelization will give clues to decide the best angular position of the sensors that will minimise the errors. Also, flux-compensating techniques can be implemented to decrease the effect of the crosstalk magnetic fields. All the numerical results obtained by the software FEM-3D have been compared with the results obtained by measurements in the LME.

3. Conclusions

In the present work we have done an analysis by the finite element method (FEM) of a measuring system based in a toroidal coil placed around a rectangular bus bar and placed near another rectangular bus bar similar to the first one. We have considered the errors associated to the non symmetry of the bar and the effect of the crosstalk of the adjacent bus bar. The simulation by the FEM has been verified by measurements in the laboratory

A system with a particular configuration has been considered and the existence of an optimum point for placing the sensor (two in reality because of the symmetry of the system) and minimizing the errors associated to the crosstalk has been deduced. Moreover a correction factor in the measurement for correcting the error introduced by the bus bar asymmetry with respect to the value of the ideal model can be established too.

4. Acknowledgements

This paper has been developed with the financial support of the University of Zaragoza (Program 2001-2002) and Ibercaja (Research Program 2003) and the Diputacion General de Aragon (Emergent group 2004).

5. References

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