



HAL
open science

Order Reduction of a Frequency Magneto-Dynamic Problem for the Calculation of Copper Losses

Rémi Jardot, Guillaume Krebs, Anas Lahlou, Francis Roy, Claude Marchand

► **To cite this version:**

Rémi Jardot, Guillaume Krebs, Anas Lahlou, Francis Roy, Claude Marchand. Order Reduction of a Frequency Magneto-Dynamic Problem for the Calculation of Copper Losses. ICEM (International Conference on Electrical Machines), Sep 2024, Torino, Italy. hal-04693389

HAL Id: hal-04693389

<https://hal.science/hal-04693389v1>

Submitted on 10 Sep 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

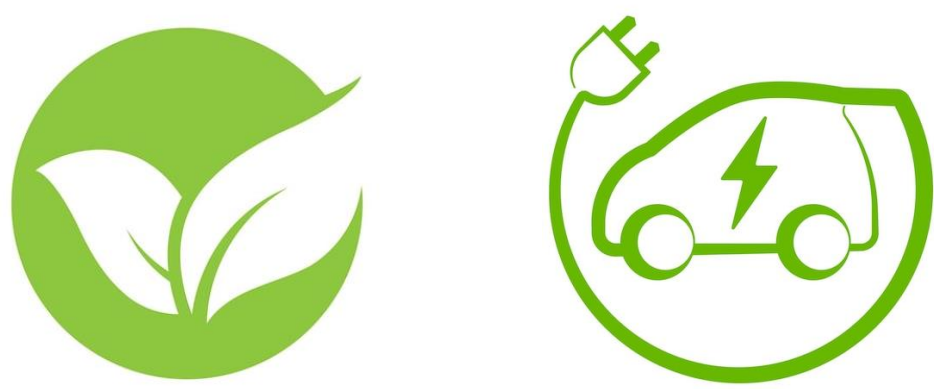
Order Reduction of a Frequency Magneto-Dynamic Problem for the Calculation of Copper Losses

Rémi Jardot¹⁻², Guillaume Krebs¹, Anas Lahlou³, Francis Roy² and Claude Marchand¹
remi.jardot@stellantis.com / remi.jardot@centralesupelec.fr

Background and objectives

Context

- Environmental issues and the growing electrification of the vehicle fleet.
- Research on disruptive electric powertrains.



Objectives

- Machine current **Harmonic content** comparison between disruptive technologies
- Accurate** estimation of losses in the electric machine
- High-order** problem resolution for optimization
- Powertrains **reduced** models

Machine losses calculation

The losses calculation is computed using the magneto-static non-linear FEA for the Iron losses and the magneto-dynamic FEA for the copper losses, and then the efficiency can be easily estimated.

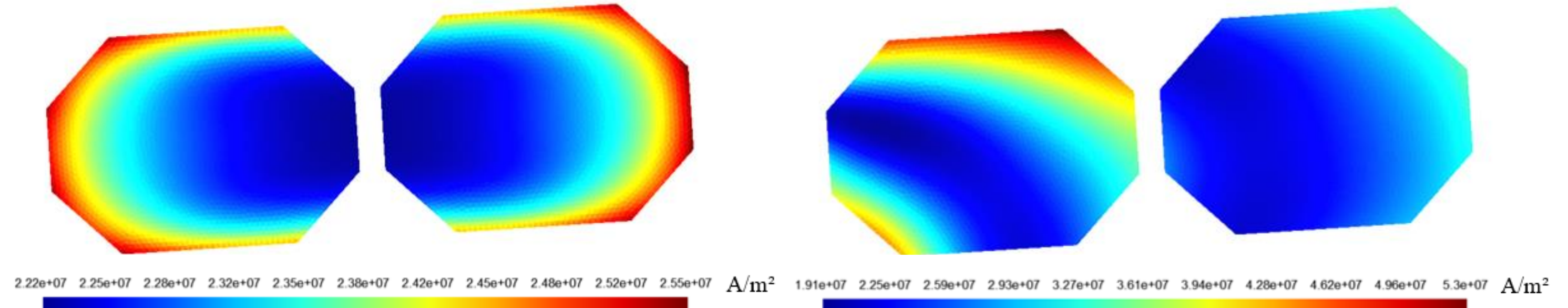


Fig.5. Current density in a slot for a rotor position with zero boundary conditions and non-zero boundary conditions

1). The **iron loss** estimation is calculated using major and minor loop detection and DC bias correction:

$$p_{Iron} = \frac{1}{T} \int_0^T k_{iGSE} \left| \frac{dB}{dt} \right|^\alpha (\Delta B)^{\beta-\alpha} dt$$

2). The **copper loss** estimation is calculated with the DC losses and the AC losses on a slot:

$$p_{Copper} = \sum_{i=1}^{N_{nodes}} \rho_i \cdot j(x_i, y_i)^2 \cdot S_i$$

Barycenter (Nm - rpm)	Standard 400V (W and efficiency)	IBIS structure (W and efficiency)	Gain (% and efficiency)
(10 - 853)	53,5 W	49,6 W	7,4 %
(15 - 5216)	748 W	462 W	38 %
(17 - 9434)	1983 W	1252 W	37 %
(57 - 4540)	1265 W	872 W	31 %
(59 - 2080)	533 W	393 W	26 %
Cycle	274 Wh	91,3	176 Wh, 94,4, 36 %, 3,10

Tab.1. Losses and efficiency comparison for the two different structures

A disruptive technology: the IBIS Battery

Comparison between some powertrains:

- Standard structure** (3-phase 400V inverter with IGBT).
- IBIS Structure** (*Intelligent Battery Integrated System*), distributed conversion function directly in the battery.

Powertrain modeling and visualization of the electric quantities on one operating point of the machine:

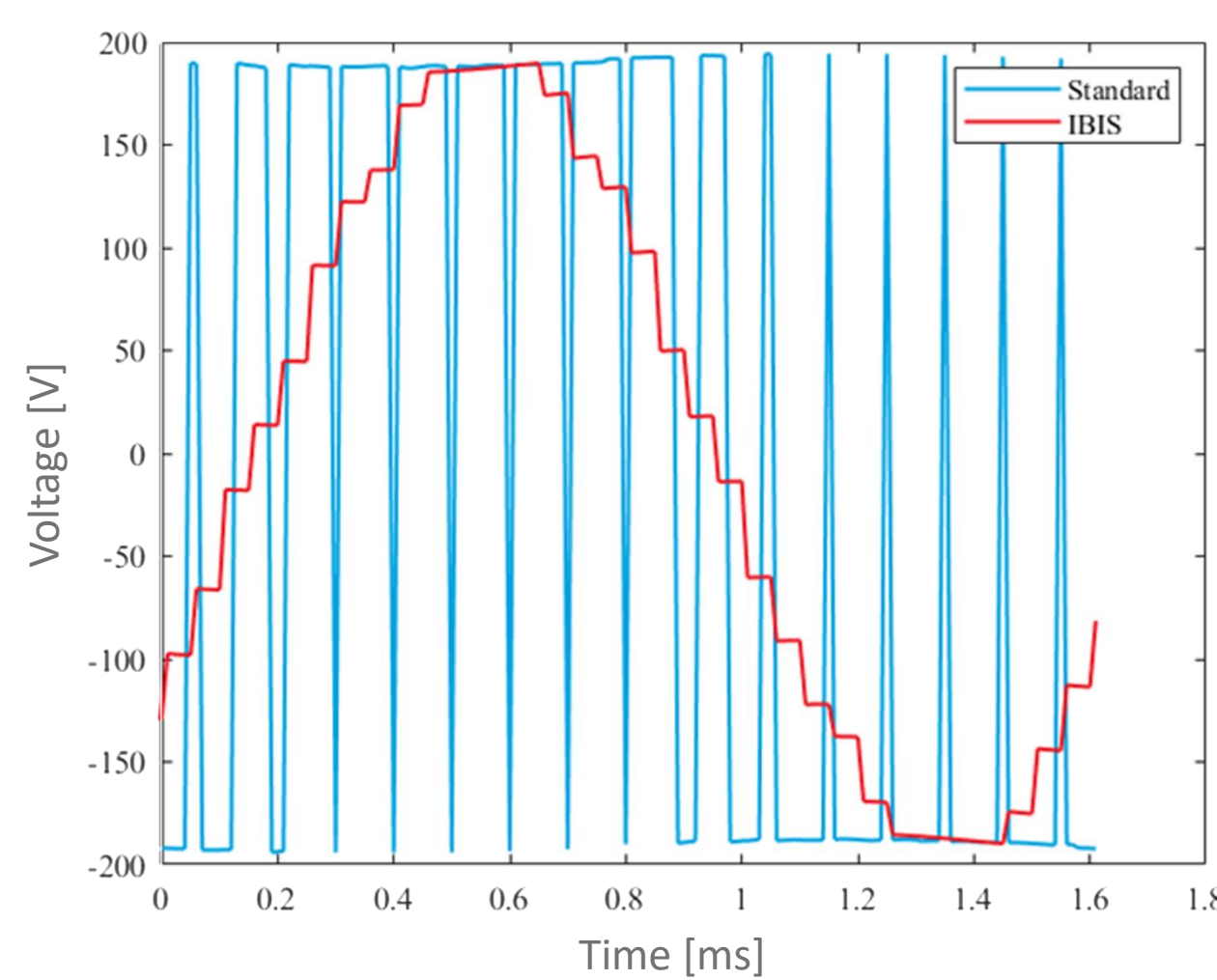


Fig.2. Phase voltage in the machine

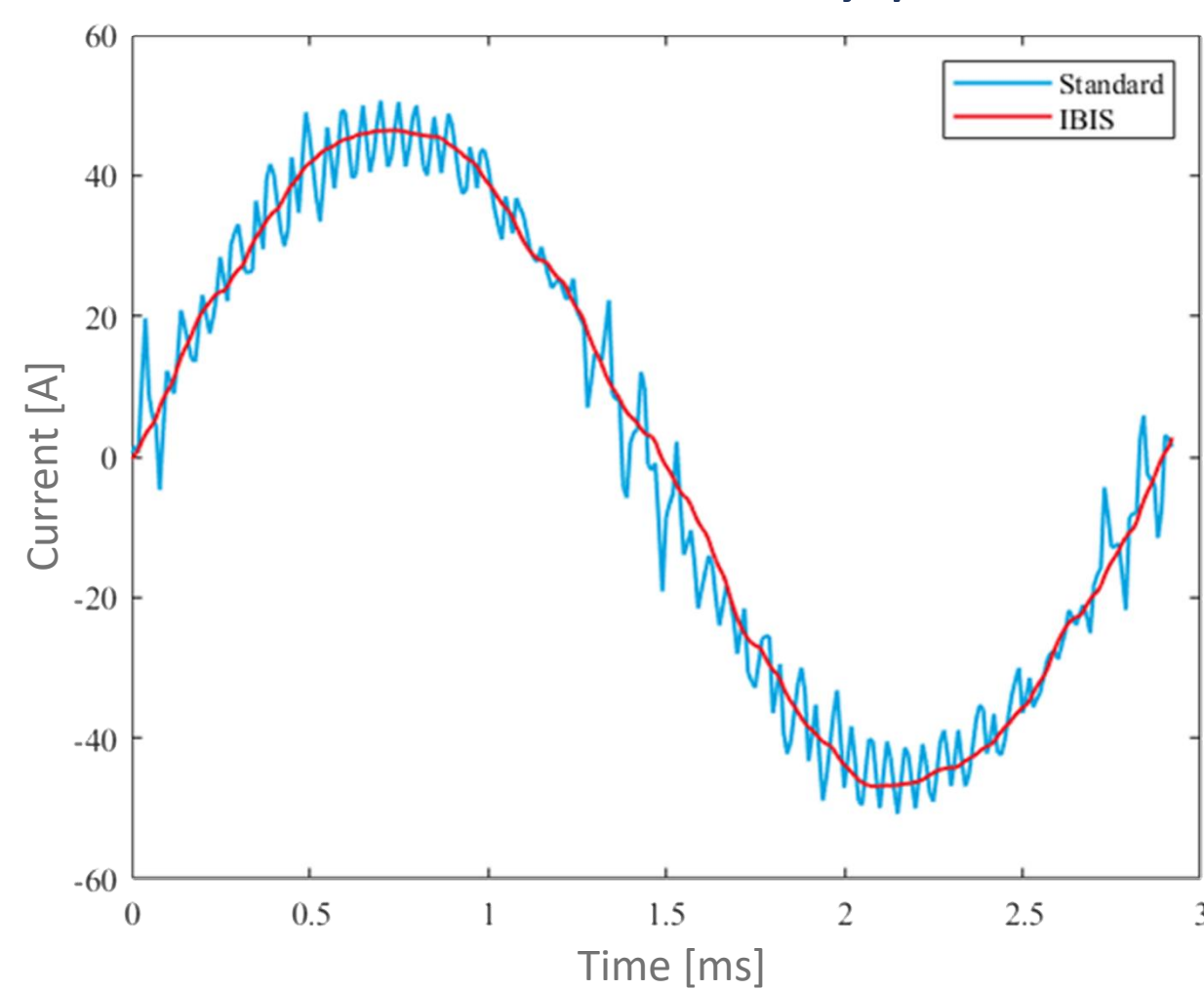


Fig.3. Phase current in the machine

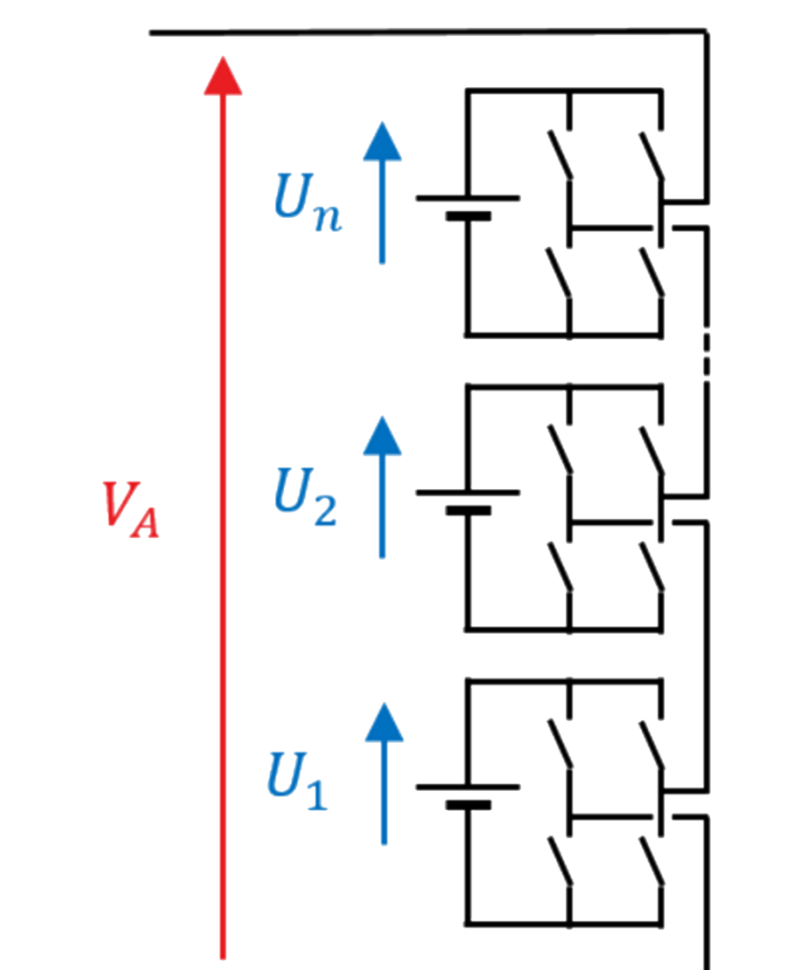


Fig.1. Scheme of an IBIS battery phase

The IBIS structure also offers a gain in phase voltage, which allows a different sizing of the powertrain.

Machine modelling

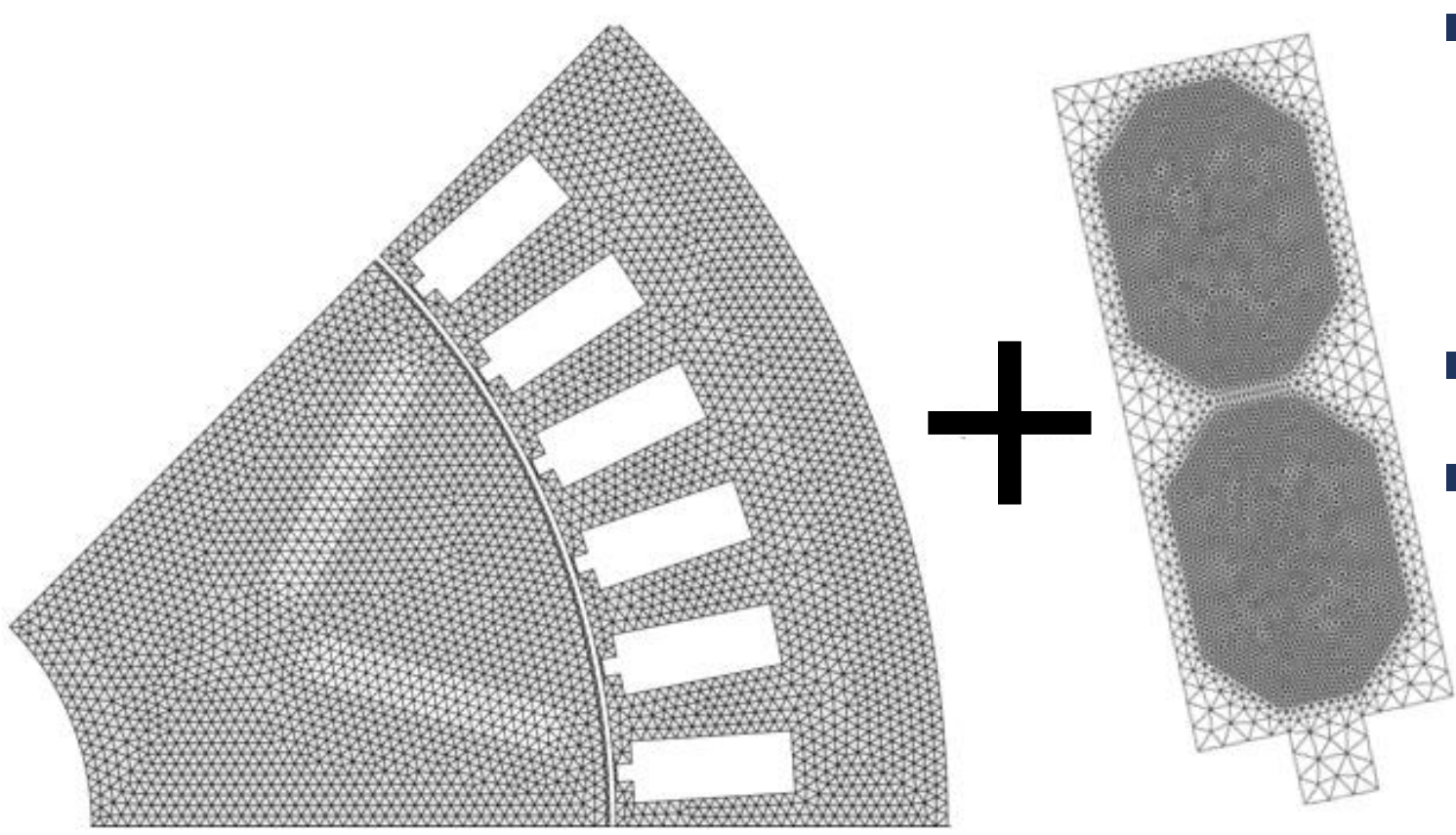


Fig.4. Mesh of the used PMSM and of one slot of the PMSM

- Permanent Magnet Synchronous Machine (PMSM) with 3 phases and 4 poles.
- Automotive applications (*Stellantis*).
- Thermal, magneto-static non-linear, magneto-dynamic, and mechanical non-linear Finite Elements Analysis (FEA).
- MORTAR interpolation method between the machine and the slot

Finite Elements Analysis with complex formulation is applied. The complex formulation for the magneto-dynamic is:

$$\begin{cases} SA + T \frac{dA}{dt} - CU_c = 0 \\ C \frac{dA}{dt} + R^{-1}U_c = -I_c \end{cases} \longrightarrow \begin{cases} (S + j\omega(T - DR^{-1}D^t)A = -DR^{-1}I \\ U_c = R^{-1}I - j\omega R^{-1}D^tA \end{cases}$$

Modal decomposition of the model

The modal decomposition use is:

$$G \cdot X = \lambda \cdot X \quad \begin{cases} X : \text{eigenvalues} \\ \lambda : \text{eigenvectors} \end{cases}$$

The testing mesh consists of 6679 nodes and 13169 triangular elements (100 mm depth, 10 mm radius, and 1,5 mm radius conductors).

Size of the problem	Time	Copper losses	Error
Temporal resolution	454 s	1.97 mW	0 %
Frequency resolution	5.03 s	1.97 mW	0 %
10 modes	2.73 s	1.66 mW	15.7 %
30 modes	3.35 s	1.92 mW	2.54 %
75 modes	6.00 s	1.95 mW	1.02 %
125 modes	9.48 s	1.96 mW	0.51 %
250 modes	16.77 s	1.96 mW	0.22 %
500 modes	39.07 s	1.97 mW	< 0.1 %
2000 modes	332.74 s	1.97 mW	< 0.1 %

Tab.1. Copper loss error for different modal analysis

Formulating the problem in the frequency domain, under the assumption of sinusoidal current in the machine, allows for a reduction in computation time by 90.

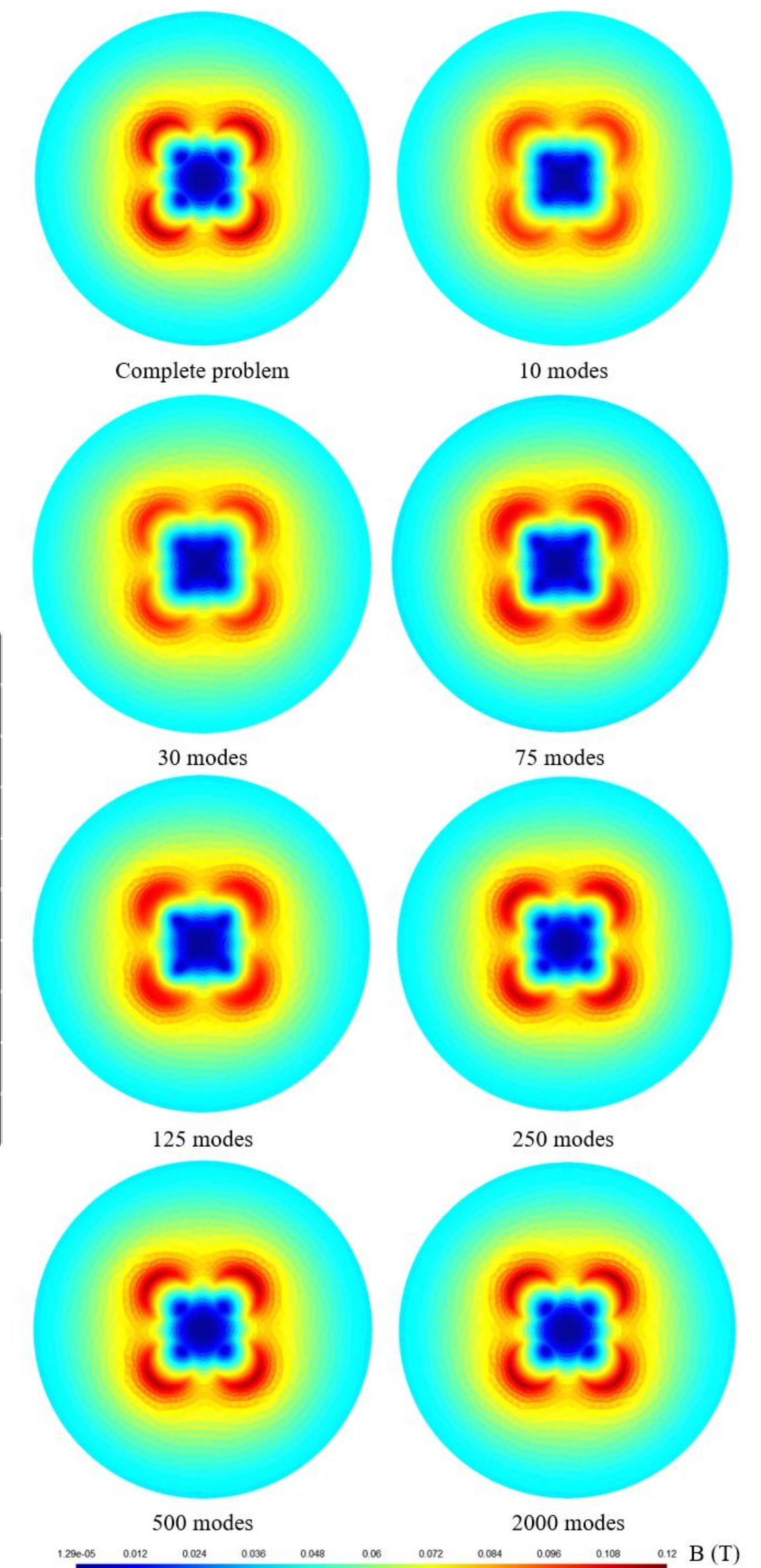


Fig.6. Flux density for the frequency domain resolution, without and with modal analysis

Conclusion and perspectives

- IBIS Structure has a better effect on the global machine efficiency: at least **25 km** more in range on a WLTC (for an e208 vehicle).
- The **modal decomposition** for the machine with different architectures needs to be verified.
- New powertrain **components** and new **architectures** need to be added to the modelization software.

¹Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, Laboratoire de Génie Electrique et Electronique de Paris, 91192, Gif-sur-Yvette, France.

²Stellantis, Centre Technique de Carrières-sous-Poissy, 212 Boulevard Pelletier, 78955, Carrières-sous-Poissy, France.

³SAFT Total Energies, 111-113 Boulevard Alfred Danet, 33074 Bordeaux, France.