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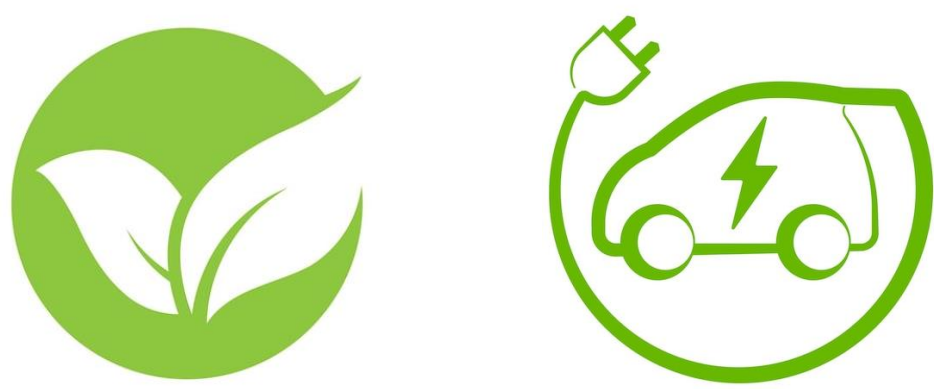
Order Reduction of a Frequency Magneto-Dynamic Problem for the Calculation of Copper Losses

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.

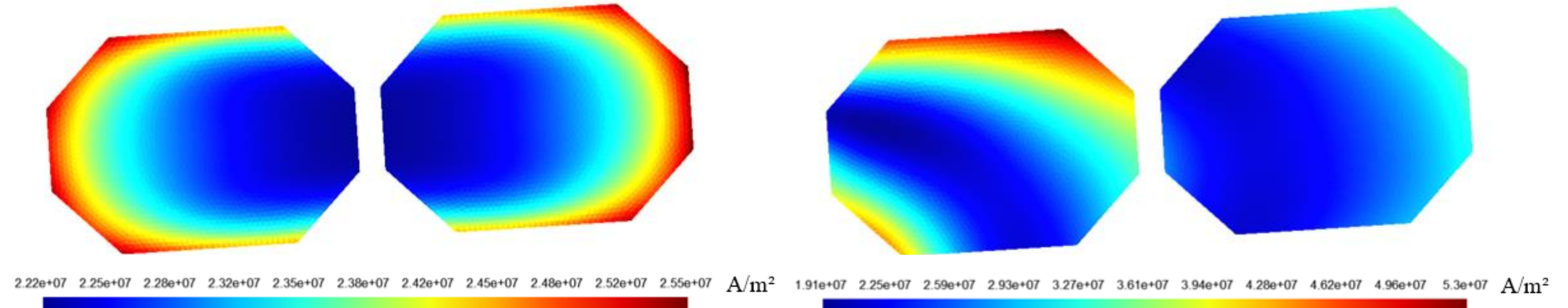


Fig.5. Current density in a slot for a rotor position with zero boundary conditions and non-zero boundary conditions

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:

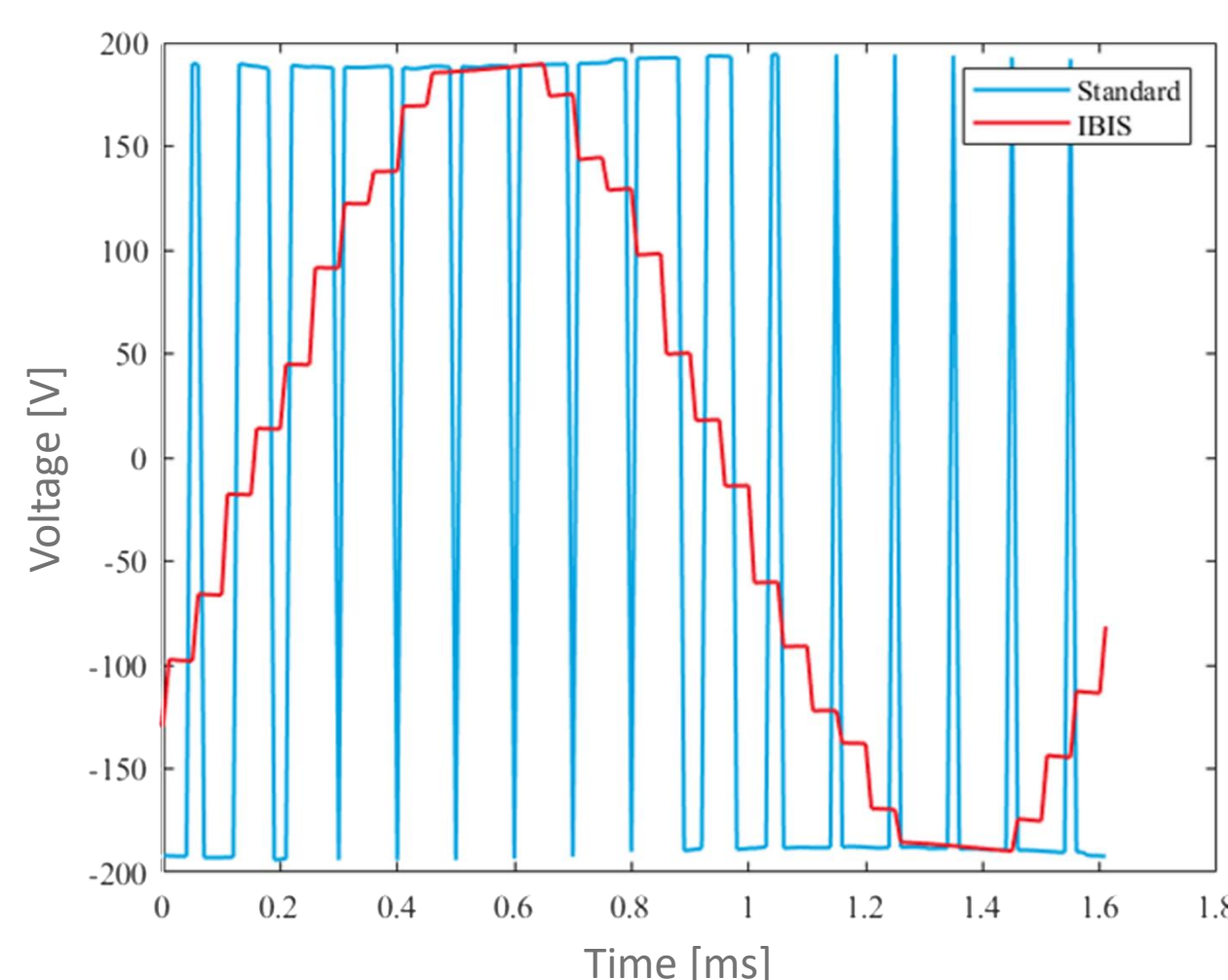


Fig.2. Phase voltage in the machine

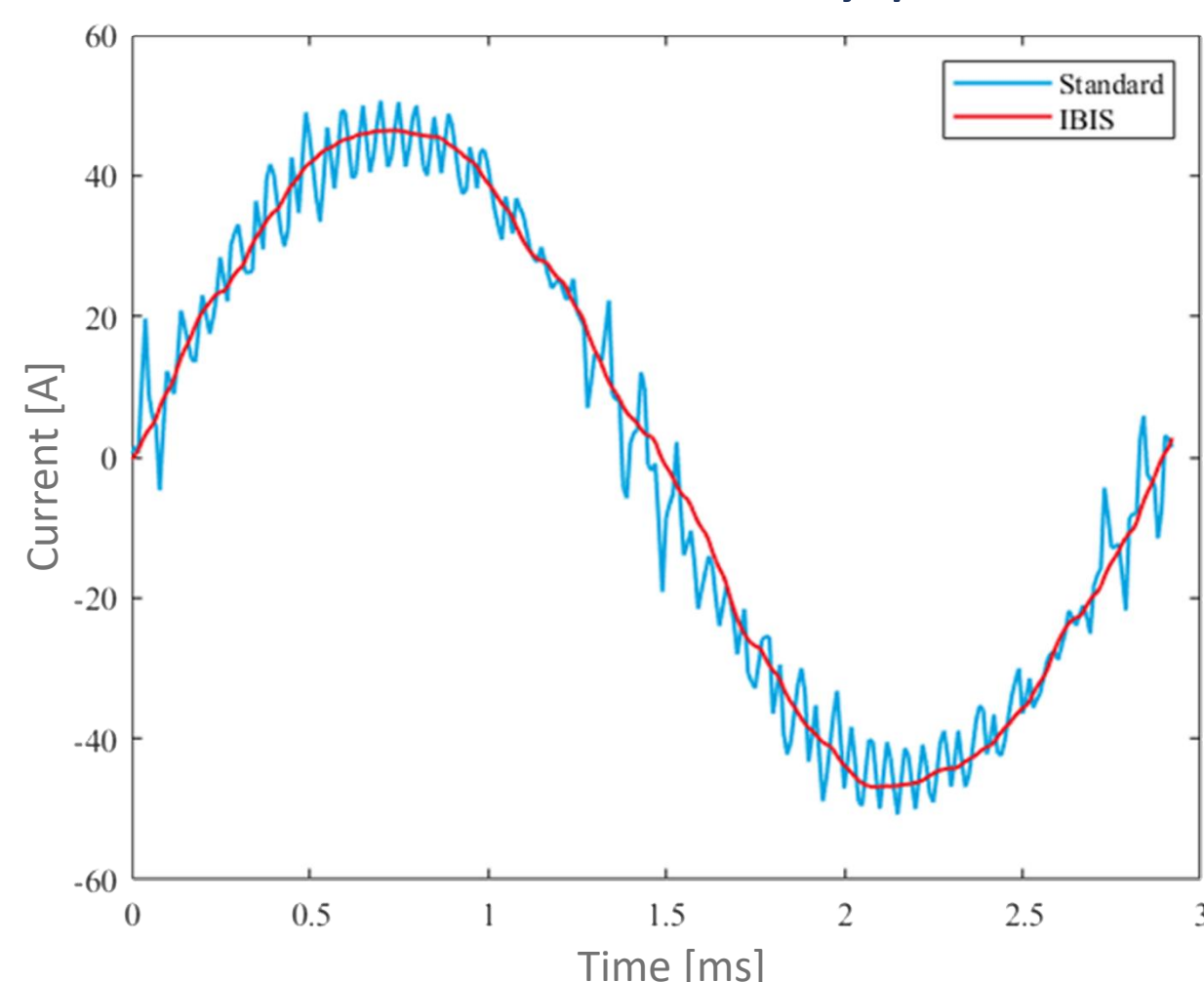


Fig.3. Phase current in the machine

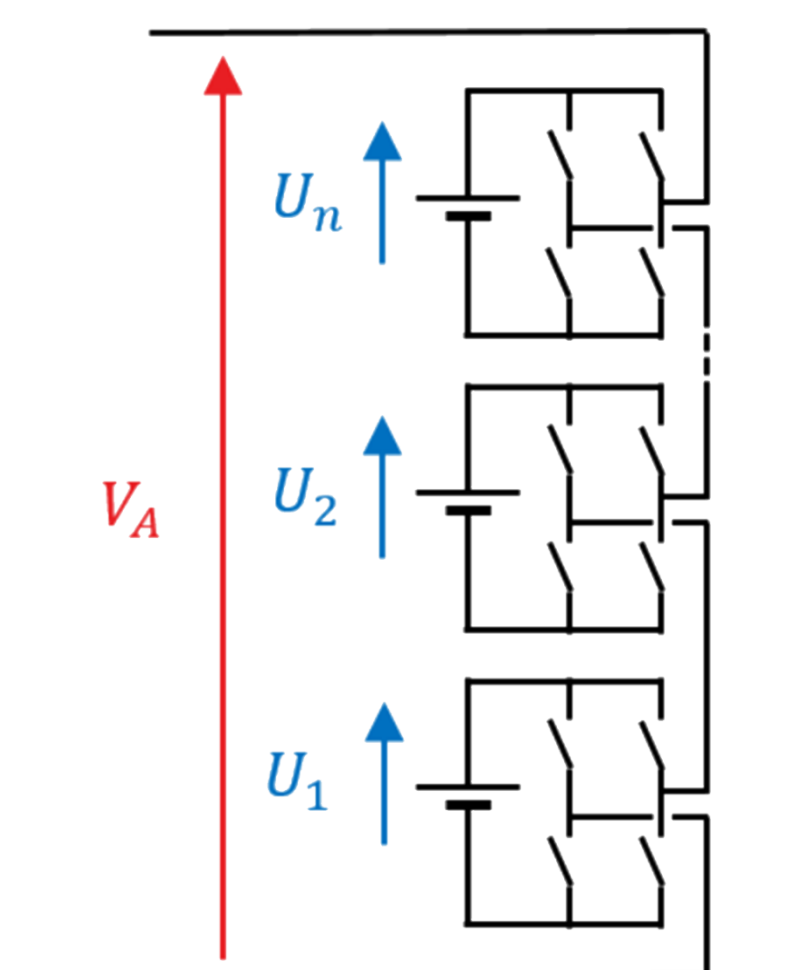


Fig.1. Scheme of an IBIS battery phase

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

Machine modelling

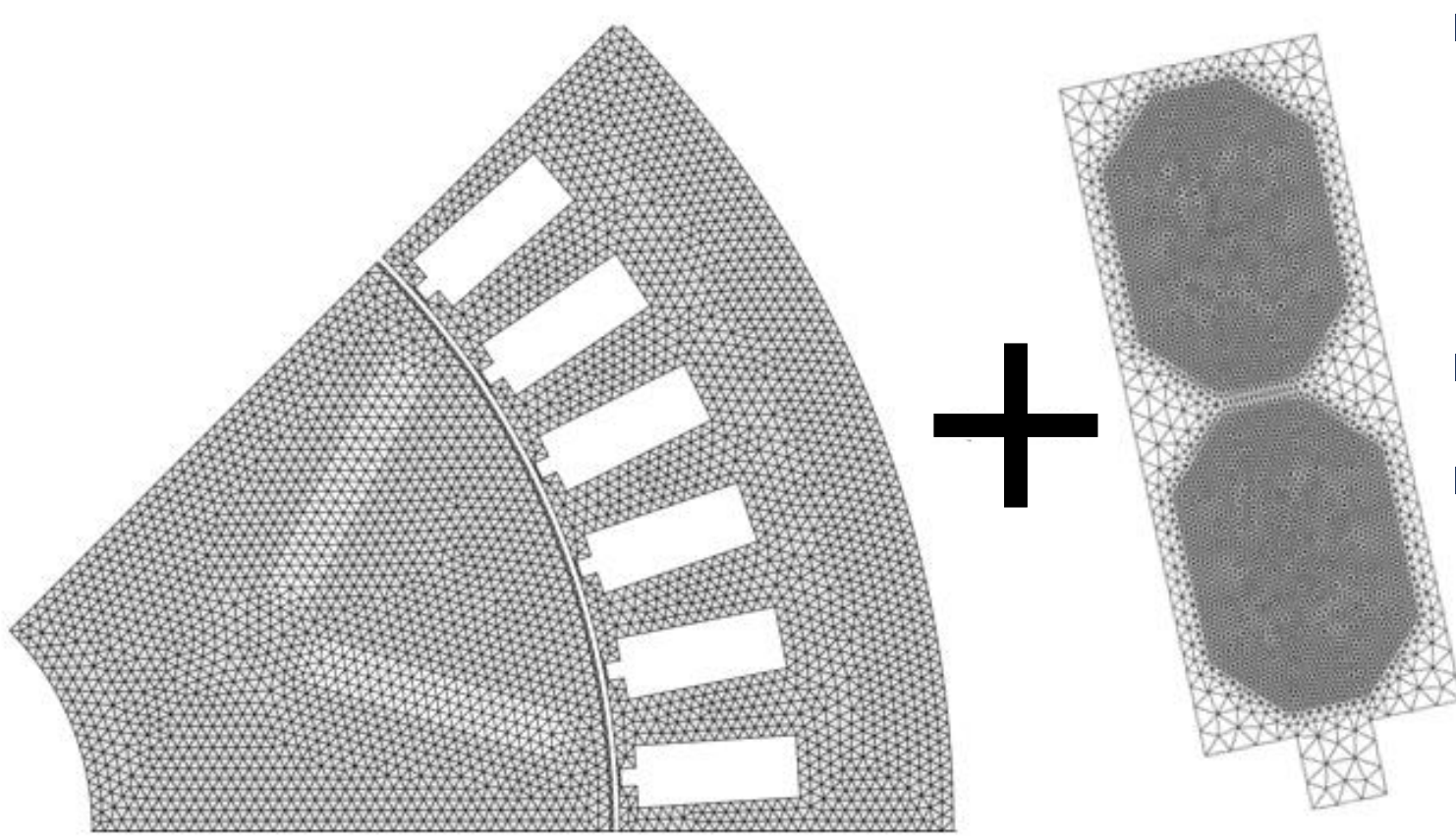


Fig.4. Mesh of the used PMSM and of one slot of the PMSM

- 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.

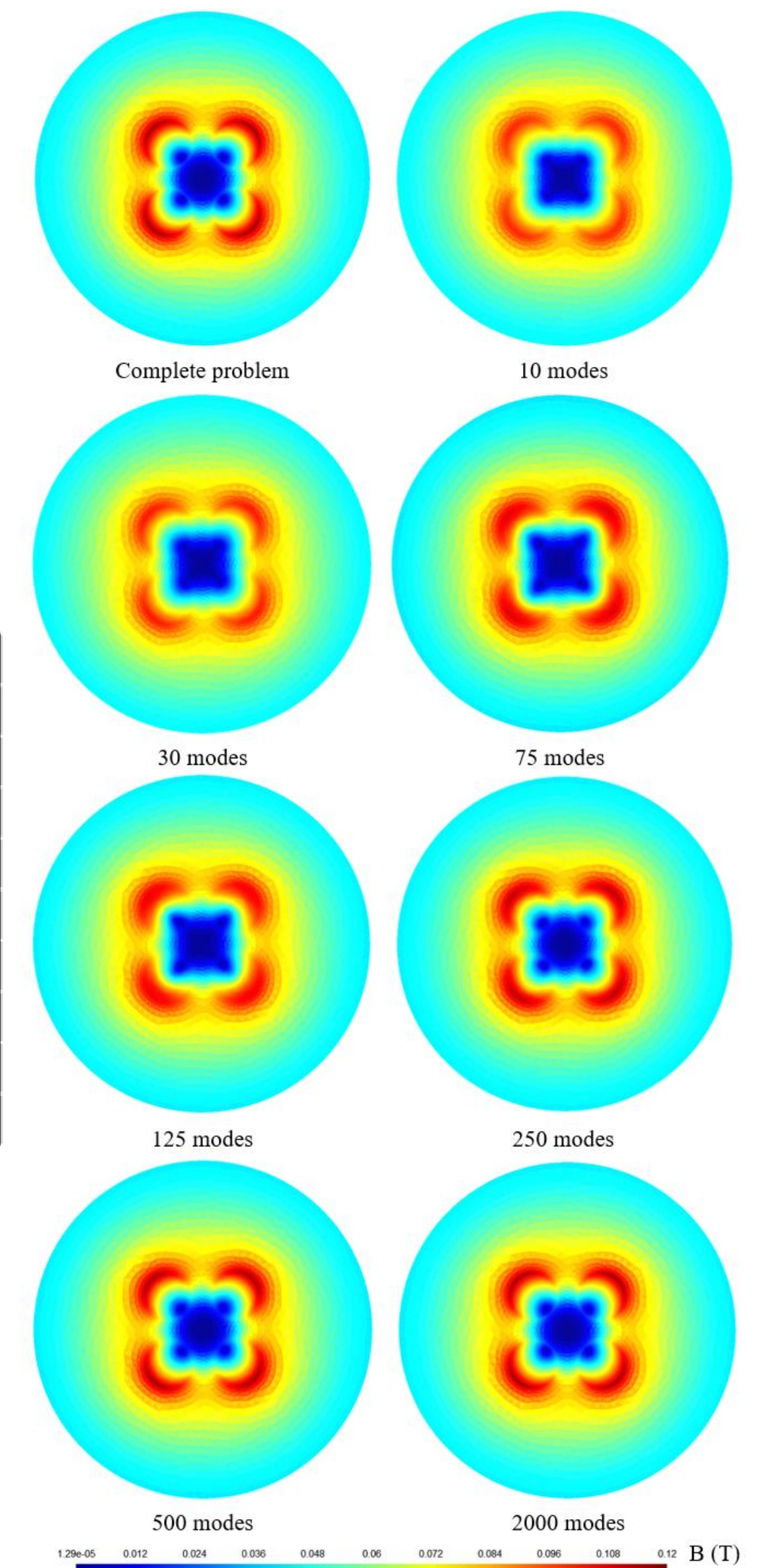


Fig.6. Flux density for the frequency domain resolution, without and with modal analysis

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.