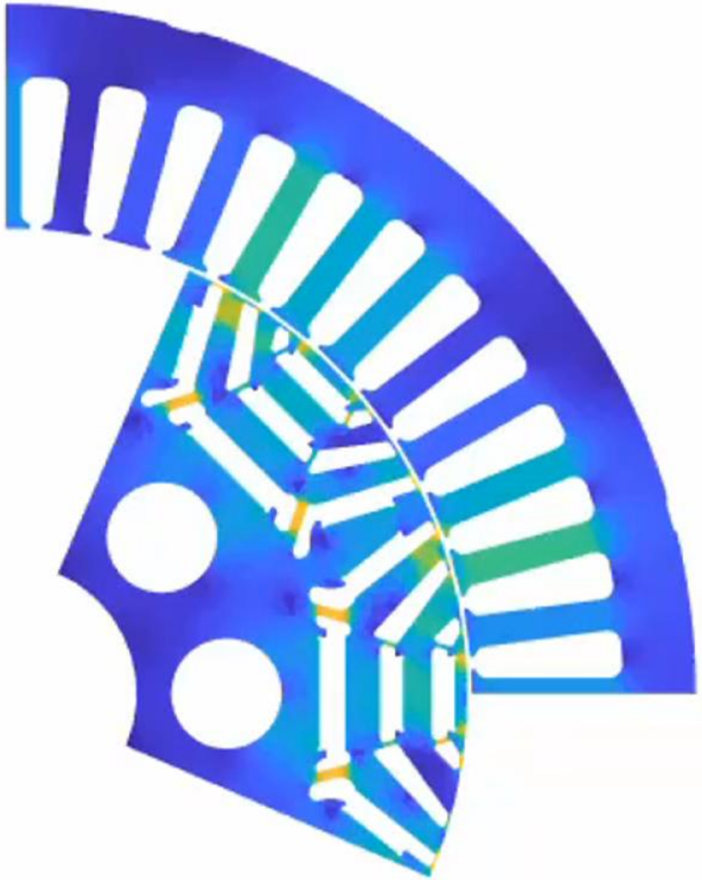
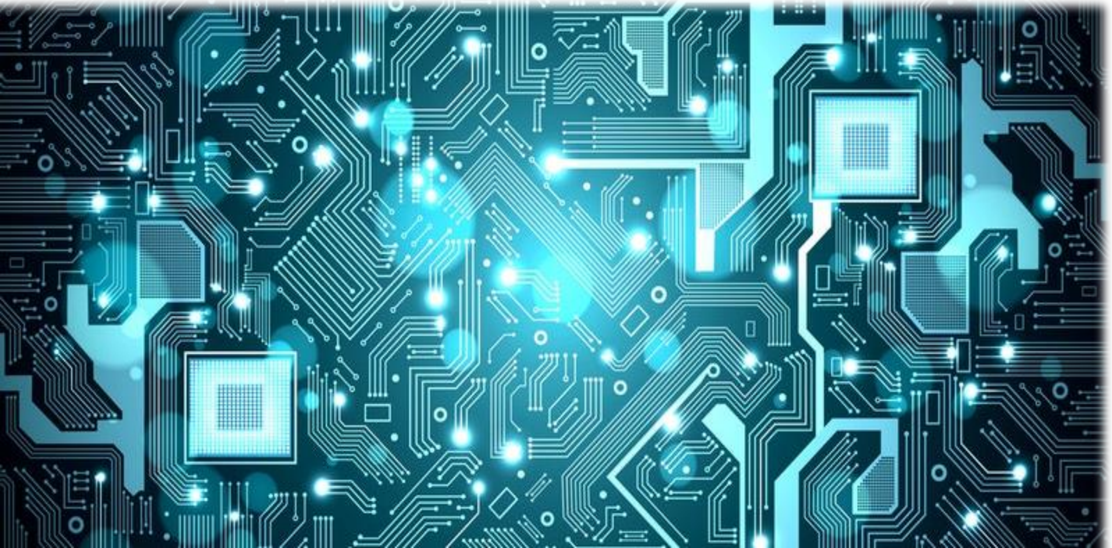


ACCURATE REDUCED MOTOR MODELS FOR POWERTRAIN SYSTEMS OPTIMIZATION



2024/06/06

FABIEN VIDAL-NAQUET

IFP Energies nouvelles

Carnot ifpen Transports Energie

SUMMARY

Sustainable mobility

- Introduction
  - IFP Energies Nouvelles : Electric System Department
- Motivation
  - Why work on model reduction?
  - Motor currents modeling issue
- Method & Results
  - Fast motor currents computation
  - Fast motor losses computation
- Conclusion

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RESEARCH & TECHNOLOGY ORGANIZATION (RTO)

A public sector **R&I** body

A **training** center

An industrial **group**

An international scope in the fields of energy, transport and the environment

1,530 people

1,078 engineers and technicians dedicated to research

RESEARCH & TECHNOLOGY ORGANIZATION (RTO)

10,205 active patents
175 basic patents
filed in 2020

13th ranking
patent filer in France
(Inpi 2020)

3rd ranking public research
centre

More than **200**
articles per year published
in international scientific
journals

Over **50** job fields,
from geologists
to engine technicians

135
doctoral students and
post-doctoral researchers

RESEARCH & TECHNOLOGY ORGANIZATION (RTO)

Sustainable mobility

Mobility activities represent :

62 on going contracts with 34 companies

26 collaborative projects involving 149 companies

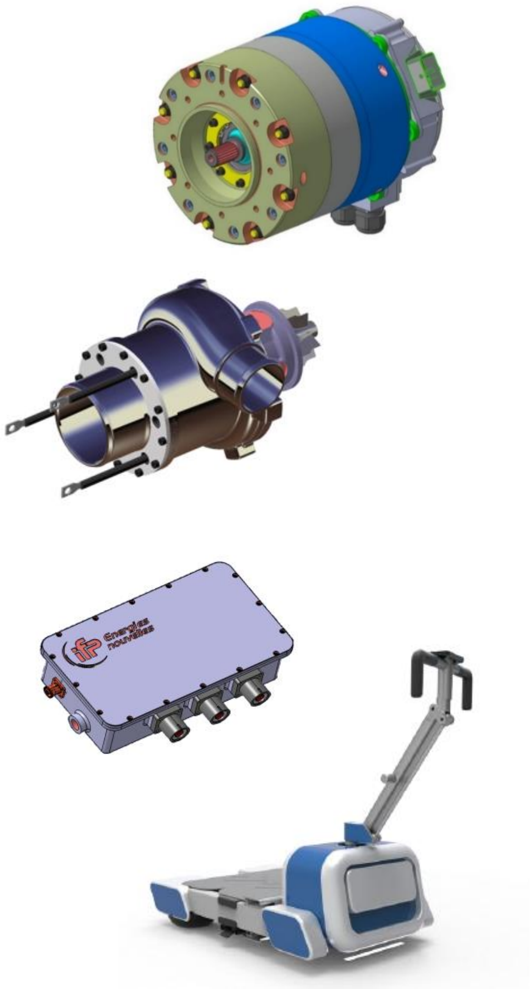
More than 293 people involved in projects

More than 35 PhD students

25 patents deposited in the year and a portfolio of 308 patents

More than 30 scientific WOS papers (excluding conference papers)

RESEARCH & TECHNOLOGY ORGANIZATION
→ ELECTRIC SYSTEMS DEPARTMENT



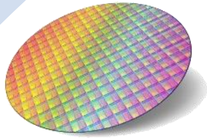
- Specify and propose innovative electric systems
- Design, simulate and prototype the electric and power electronics components
- Control and optimize the electric systems on their whole operating area
- Evaluate and validate the electric systems on dedicated experimental facilities

RESEARCH & TECHNOLOGY ORGANIZATION
→ ELECTRIC SYSTEMS DEPARTMENT

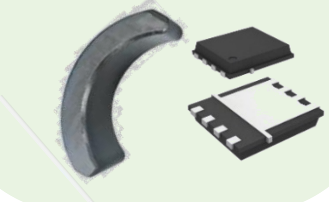
Sustainable mobility

Partnerships

Materials



Advanced components or on shelf



Parts design

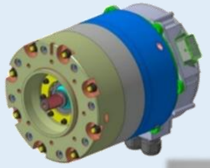
→ Active parts (Radial, Axial…)

→ Power stages (SiC/GaN)

→ e-Motors (48-800V)

→ Inverters

→ Fuel Cell DC/DC

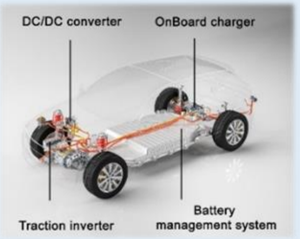


TRL 7

eDrive Systems

→ For xEV

→ For FCEV



TRL 9

Partnerships

Custom markets

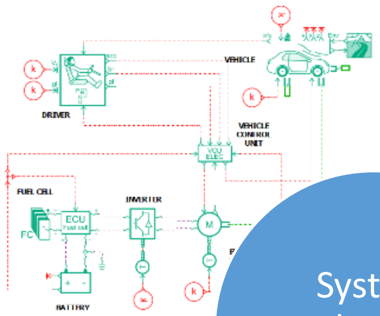
Inverters for bench testing

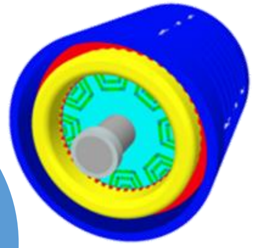
Industrial support

Towards automotive traction and fuel cell applications

Carnot ifpen Transports Energie

Sustainable mobility





ELECTRIC SYSTEMS

System analysis and simulation

Motors design and simulation (EM, thermal)

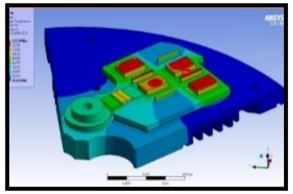
Electronics design and simulation (EM, thermal)

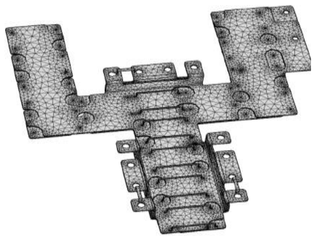
Mechanical design

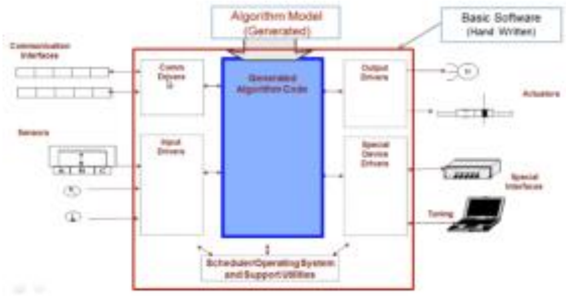
Electric motor and electronics prototyping

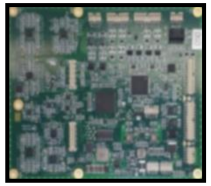
Control design and prototyping

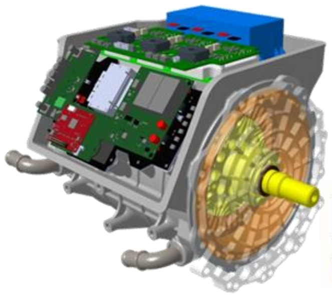
Experimental validation











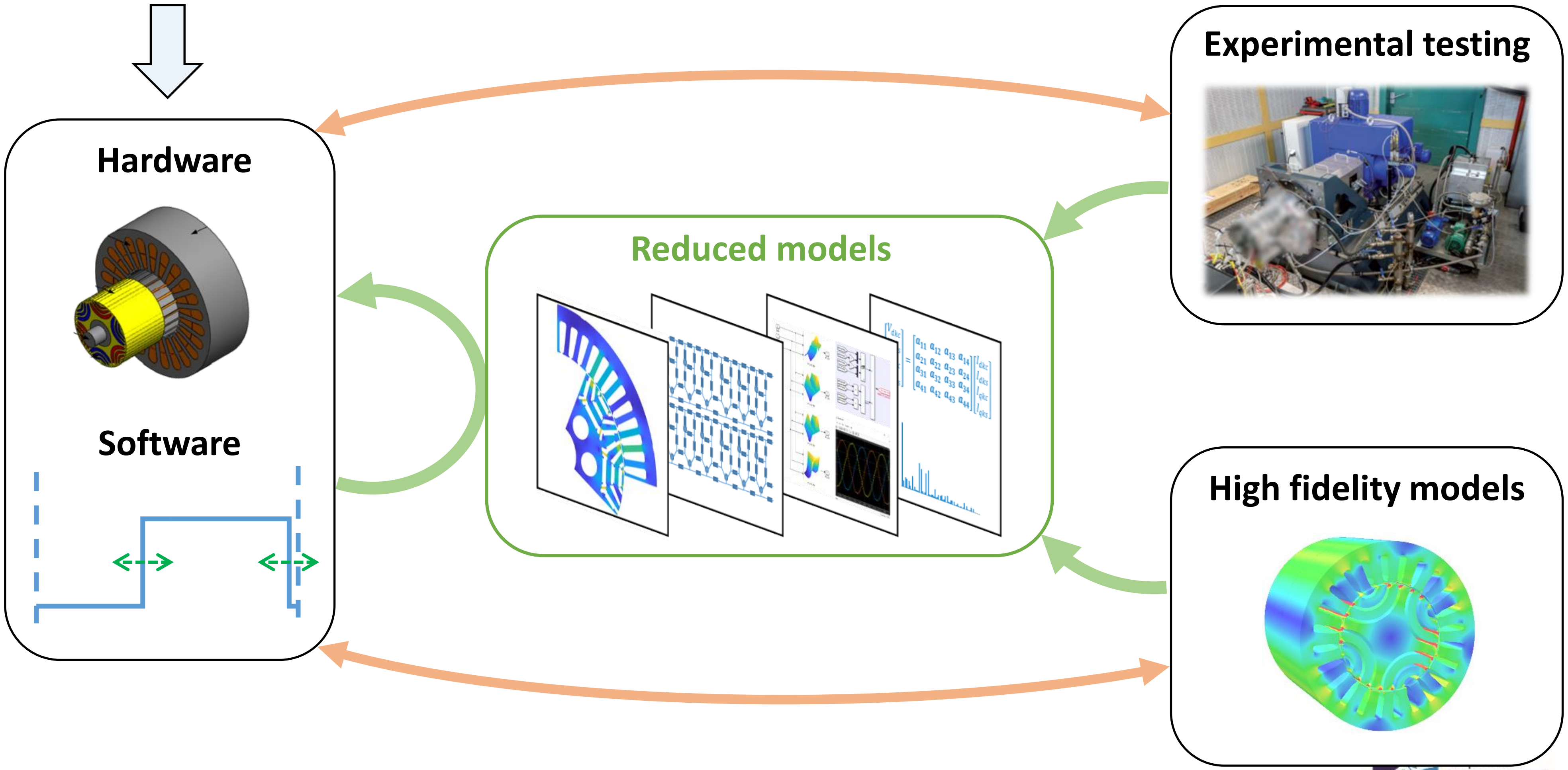
SUMMARY

Sustainable mobility

MOTIVATION

Sustainable mobility

Powertrain optimization:
Efficiency, noise, ecological impact, compactness, durability…



MOTIVATION

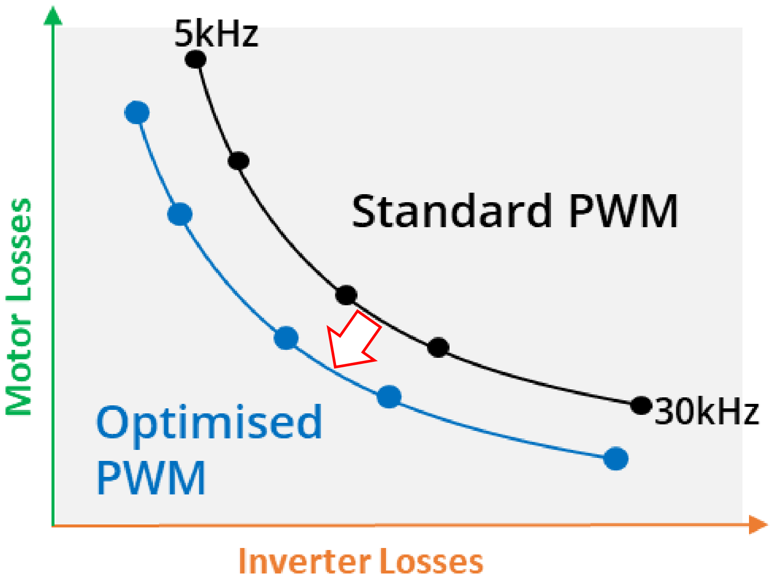
Sustainable mobility

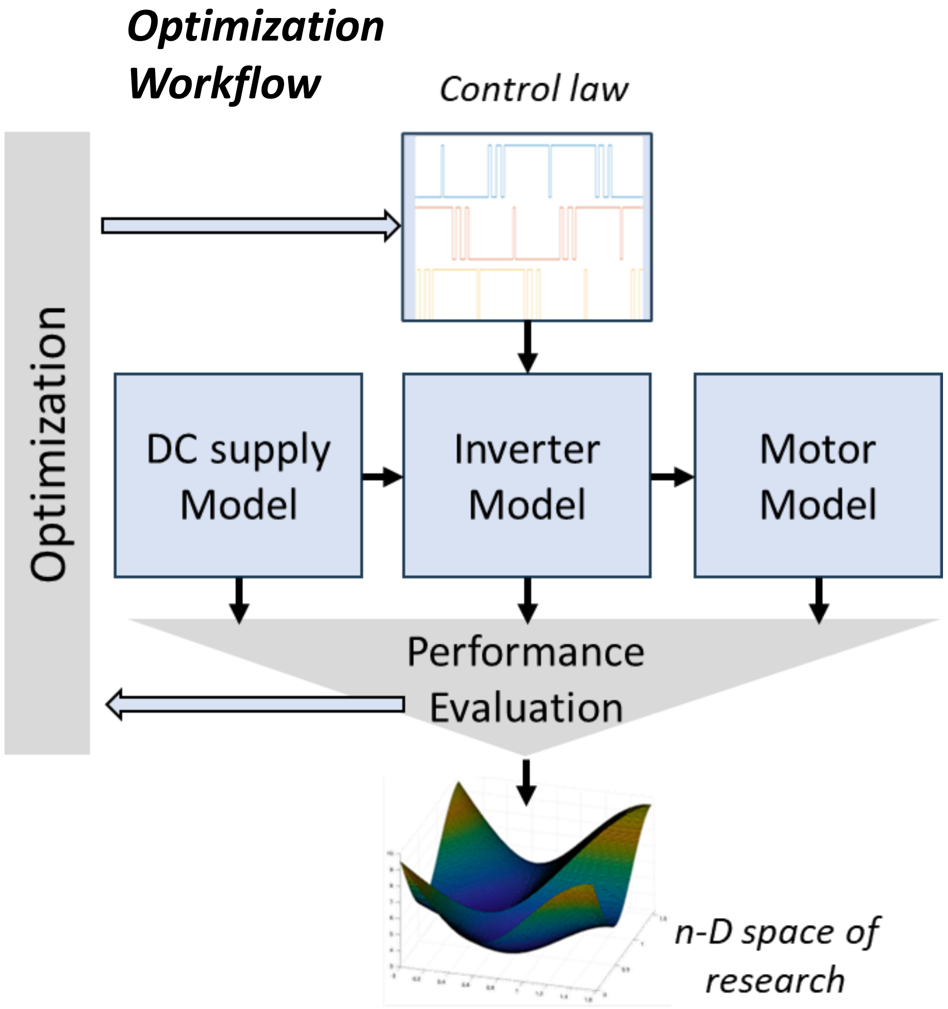
Replace control laws bench evaluation with simulation

(as much as possible…)

→ Performance criteria : efficiency and constraints (DC ripple, NVH, Torque ripple, CPU load, etc.)

→ Usually evaluated on the bench due to system complexity → But degrees of freedom are too many

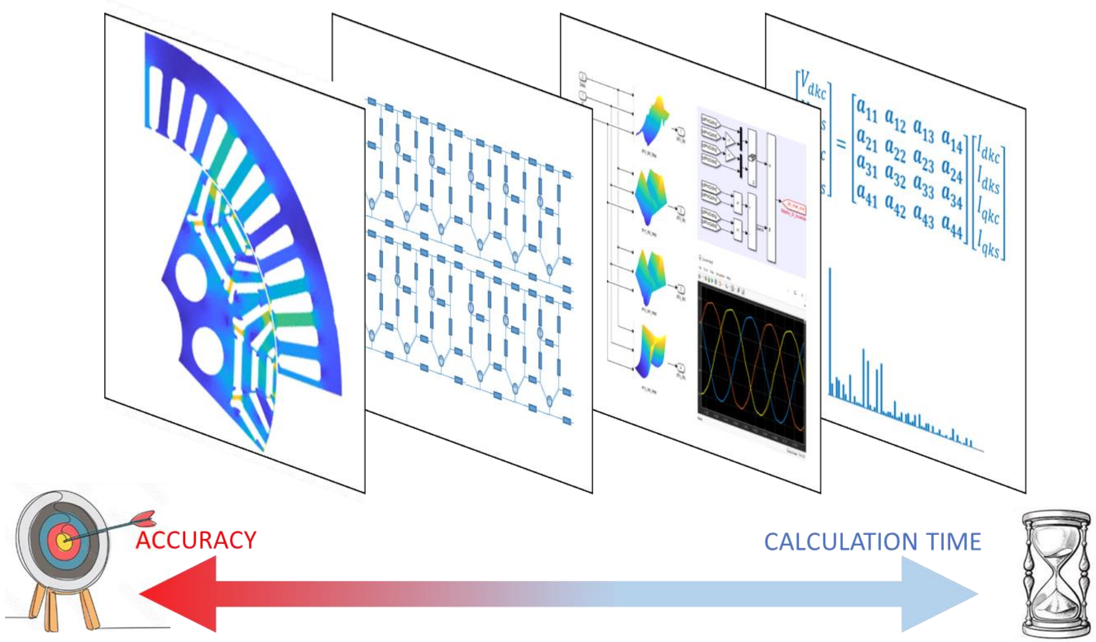


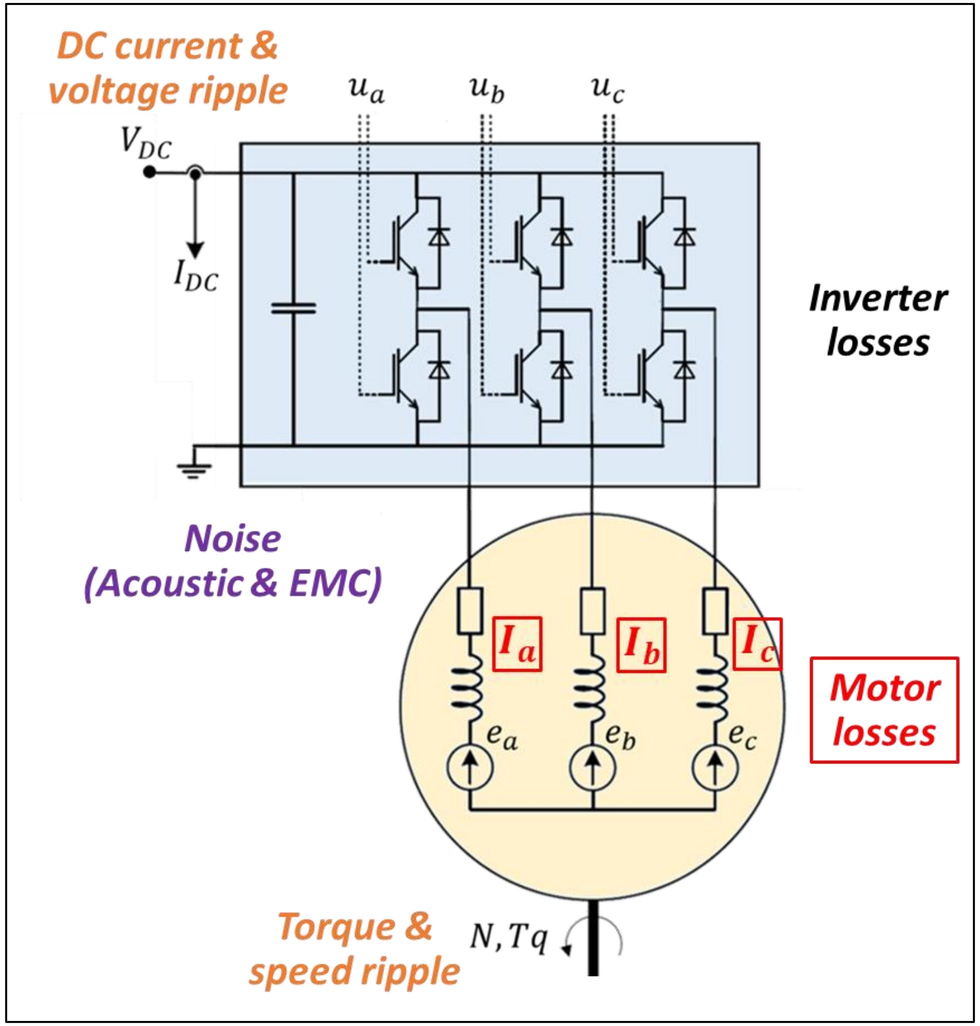


Sustainable mobility

Objective: best possible time/accuracy trade-off for

1) Computation of accurate motor **currents** depending on PWM control
2) Computation of accurate motor **losses** depending on current shapes





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IFP Energies nouvelles

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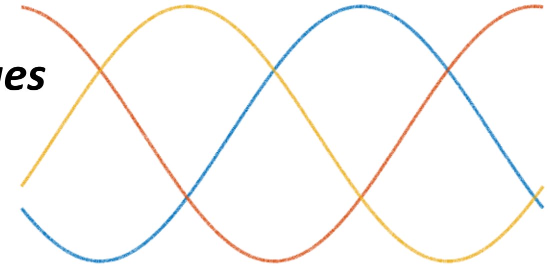
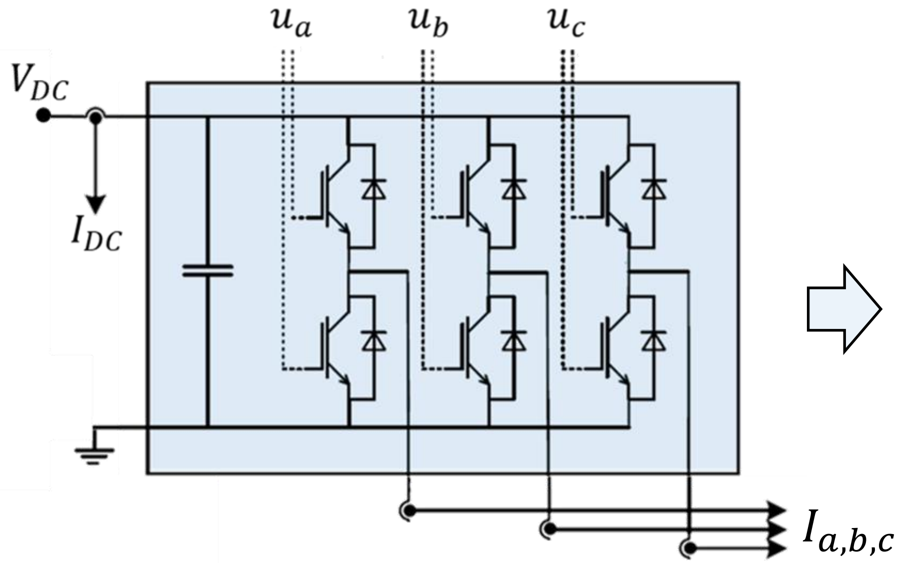
MOTIVATION – MOTOR CURRENTS & PWM

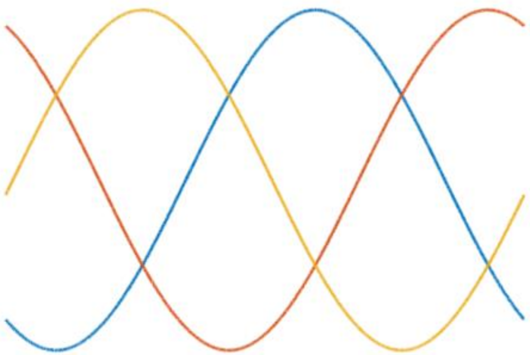
Motor currents shapes modeling: ideal case

Applied voltages (sinusoïdal)

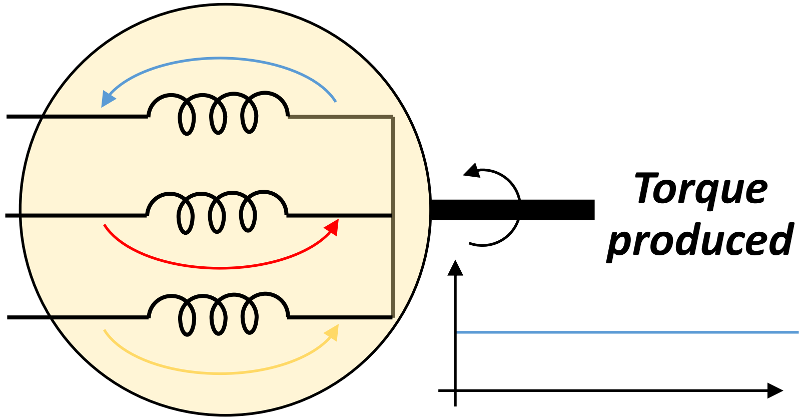


Torque request





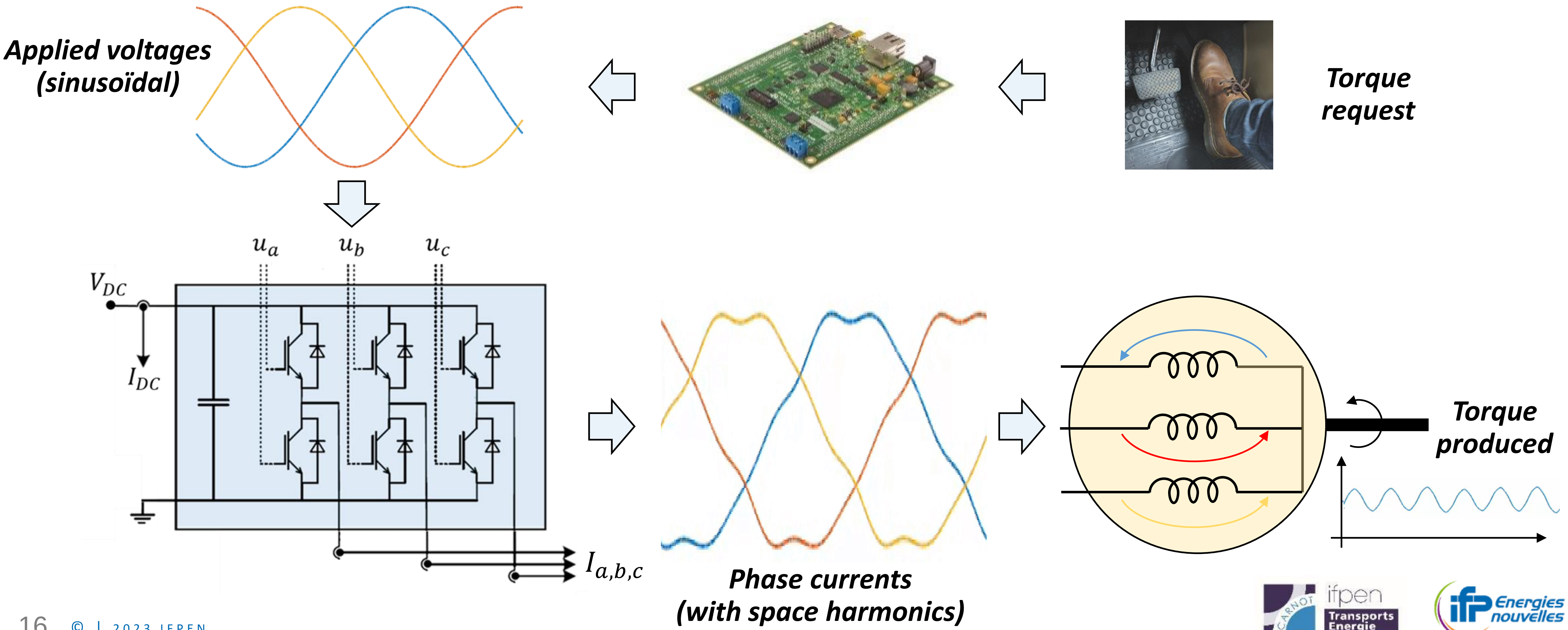
Phase currents (ideal case)



MOTIVATION – MOTOR CURRENTS & PWM

Sustainable mobility

Motor currents shapes modeling: **with motor space harmonics**

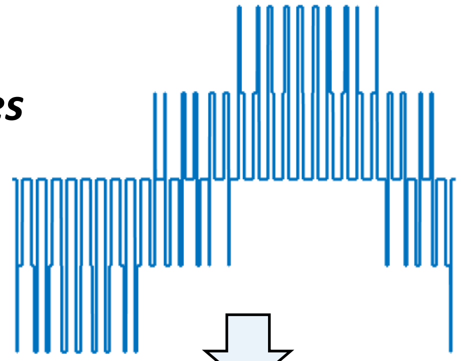


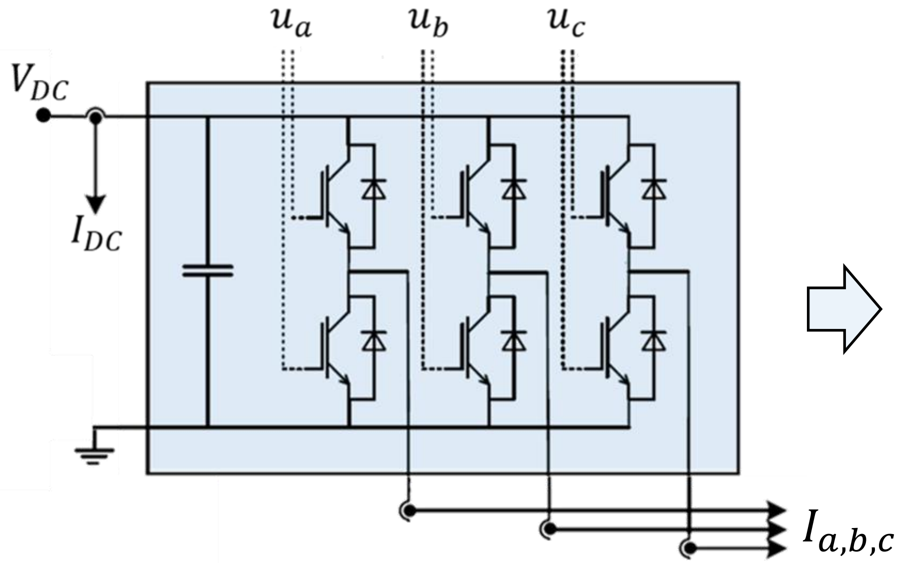
MOTIVATION – MOTOR CURRENTS & PWM

Sustainable mobility

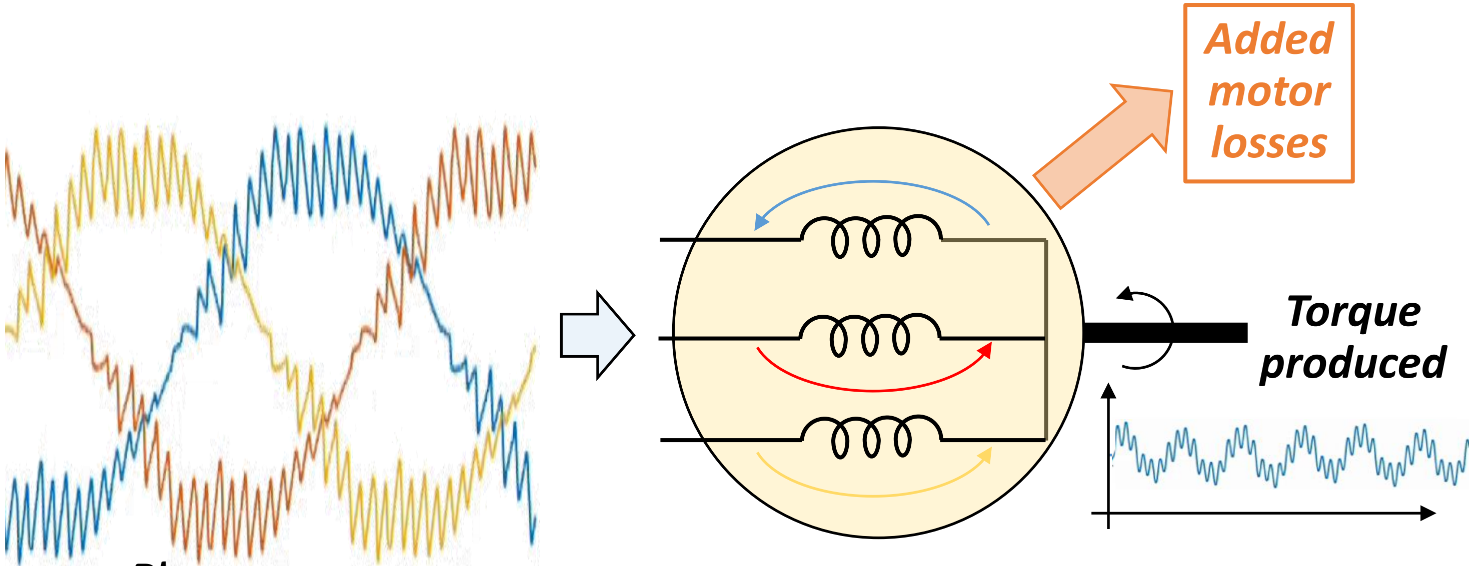
Motor currents shapes modeling: **with space and switching harmonics**

Applied voltages (real)





Torque request

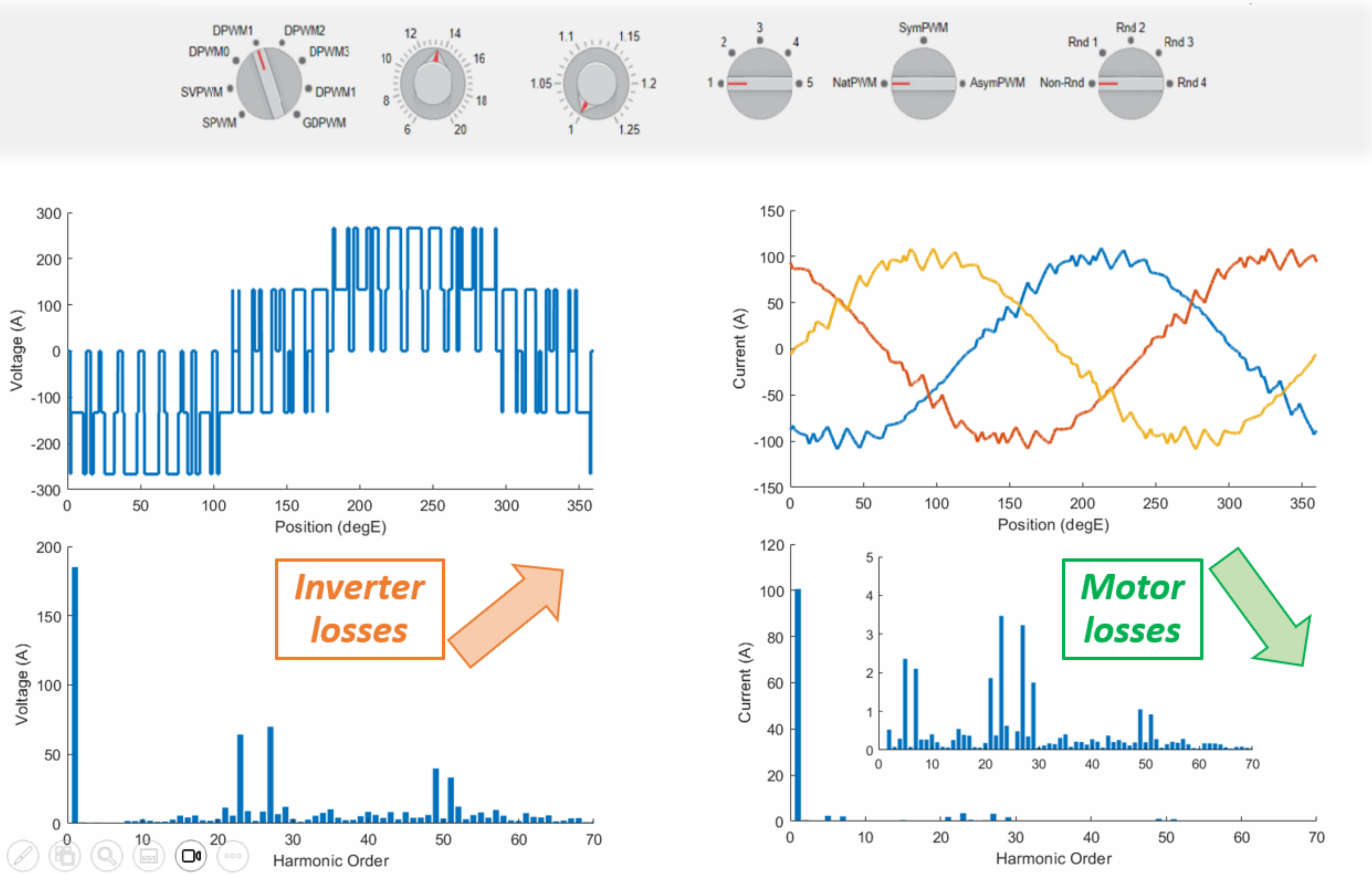


Phase currents (with space & switching harmonics)

MOTIVATION – MOTOR CURRENTS & PWM

Sustainable mobility

Motor currents shapes modeling: **effect of PWM setup & frequency increase**



PWM setup implies infinite possibilities

→Switching frequency (fixed, dynamical, random, etc.)

→Zero-sequence component (SVPWM, DPWM, THIPWM...)

→Overmodulation level, etc.

Compute motor losses is very time consuming

→ Run accurate simulations in a shorter time is a game changer here

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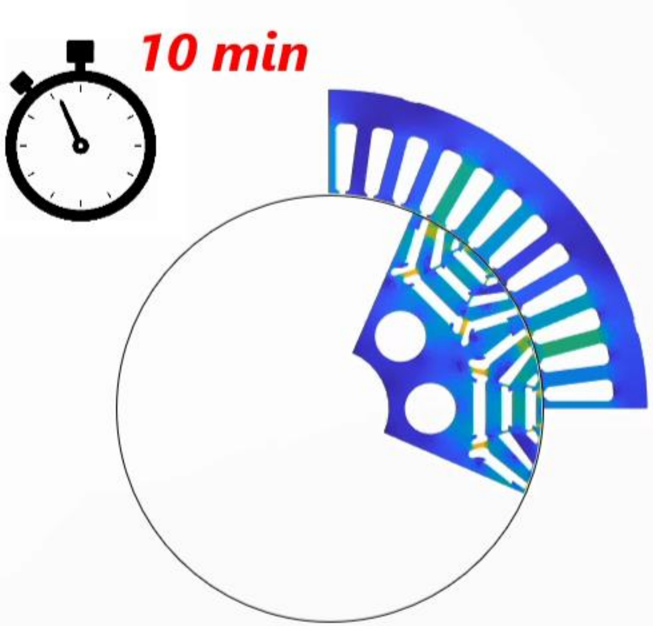
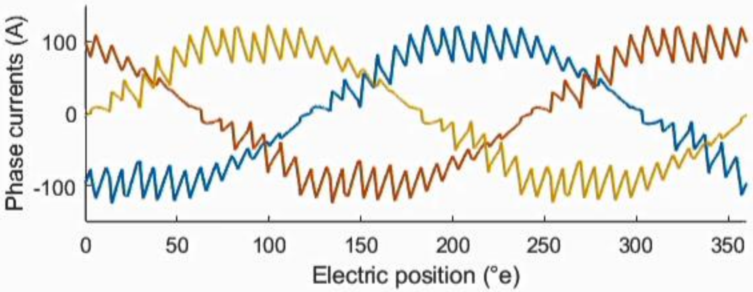
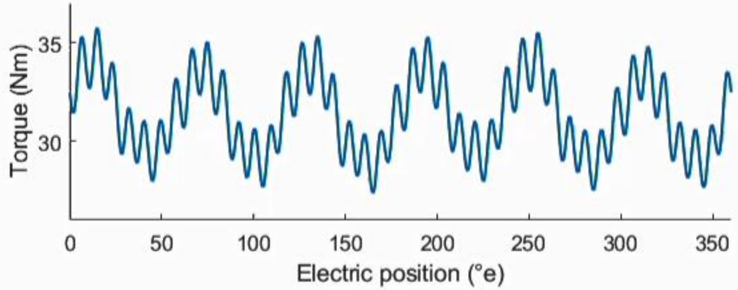
Finite Elements

10 min

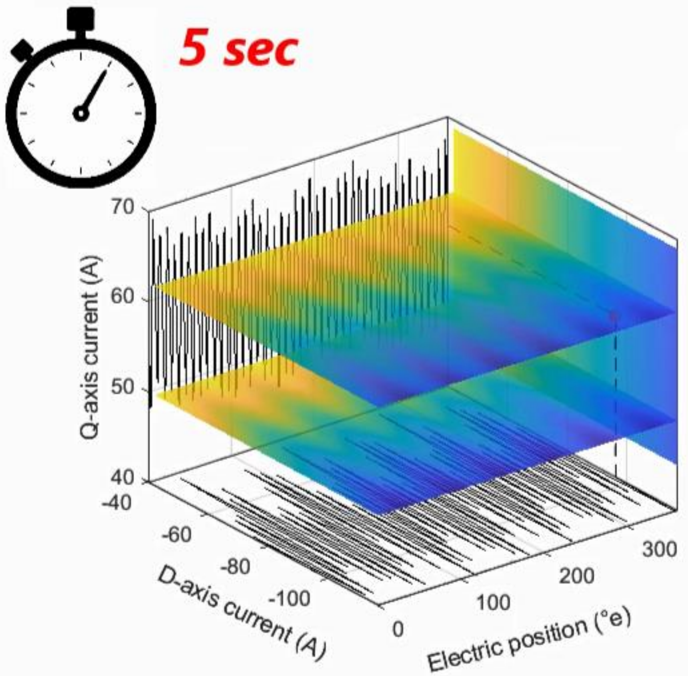


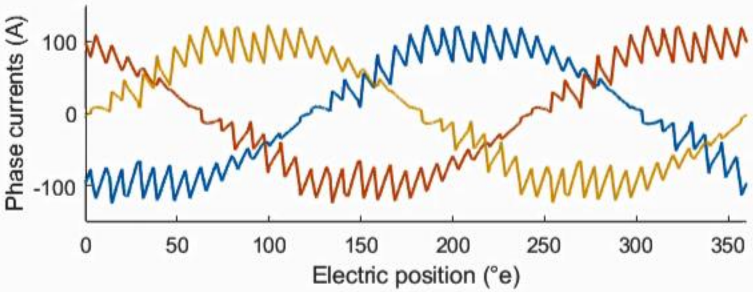


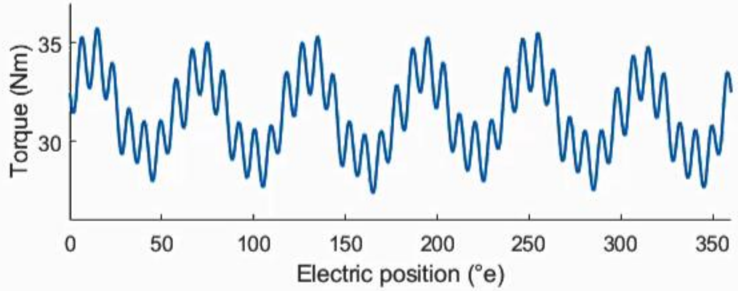


Time-based reduced model

5 sec

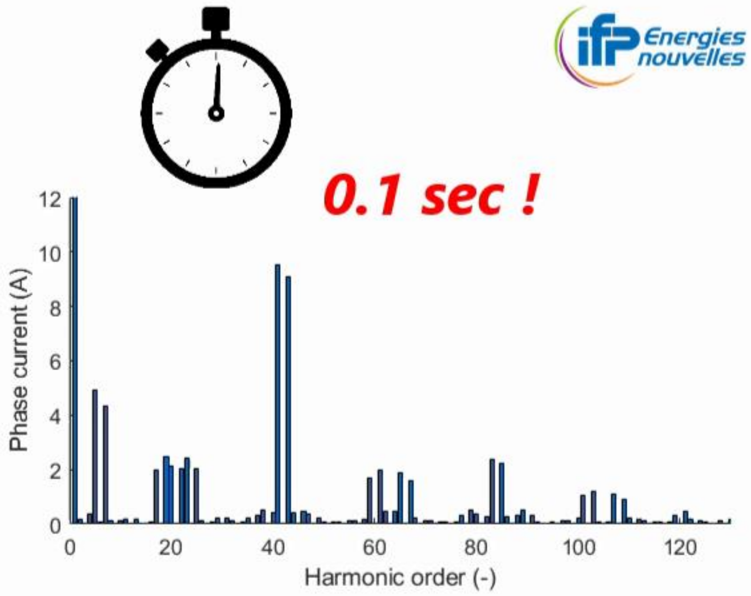


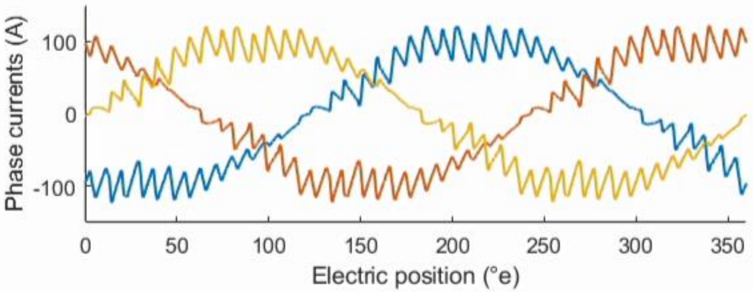


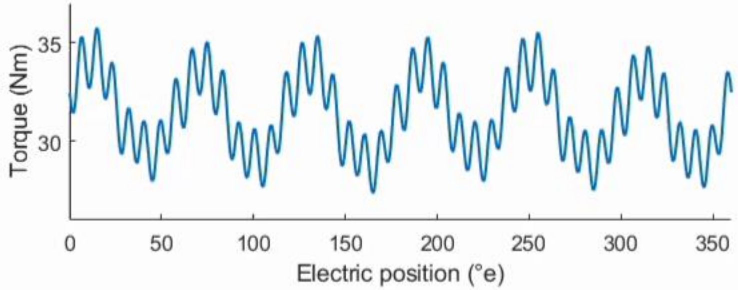


Frequency-based reduced model

0.1 sec !





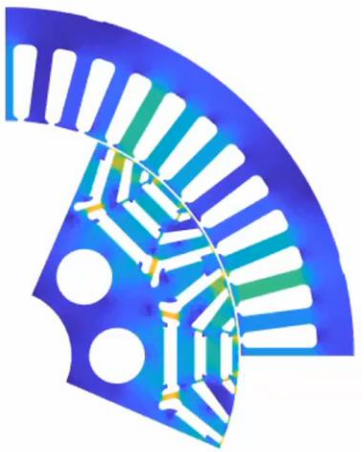


RESULTS – MOTOR CURRENTS COMPUTATION

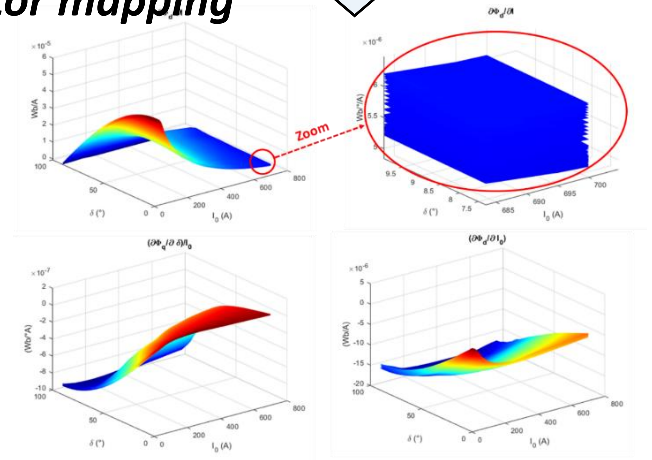
Sustainable mobility

Methodology: From finite elements to time & frequency based models

Finite elements computations



Motor mapping



Frequency equations

$$\begin{bmatrix} V_{dkc} \\ V_{dks} \\ V_{qkc} \\ V_{qks} \end{bmatrix} - \omega_e \begin{bmatrix} -\Phi_{qHkc} \\ -\Phi_{qHks} \\ \Phi_{dHkc} \\ \Phi_{dHks} \end{bmatrix} + k\omega_h \begin{bmatrix} -\Phi_{dHks} \\ \Phi_{dHkc} \\ -\Phi_{qHks} \\ \Phi_{qHkc} \end{bmatrix} = \begin{bmatrix} R-\omega_e l_{qd} & -k\omega_h l_{dd} & -\omega_e l_{qq} & -k\omega_h l_{dq} \\ k\omega_h l_{dd} & R-\omega_e l_{qd} & k\omega_h l_{dq} & -\omega_e l_{qq} \\ \omega_e l_{dd} & -k\omega_h l_{qd} & R+\omega_e l_{dq} & -k\omega_h l_{qq} \\ k\omega_h l_{qd} & \omega_e l_{dd} & k\omega_h l_{qq} & R+\omega_e l_{dq} \end{bmatrix} \begin{bmatrix} I_{dkc} \\ I_{dks} \\ I_{qkc} \\ I_{qks} \end{bmatrix}$$

Time equations

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{\partial \phi_d}{\partial i_d} & \frac{\partial \phi_d}{\partial i_q} \\ \frac{\partial \phi_q}{\partial i_d} & \frac{\partial \phi_q}{\partial i_q} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d\theta_e}{dt} \begin{bmatrix} \frac{\partial \phi_d}{\partial \theta_e} - \phi_q \\ \frac{\partial \phi_q}{\partial \theta_e} + \phi_d \end{bmatrix}$$

→Compared against magneto-dynamic simulation (Maxwell software)

→Compared against experimental data

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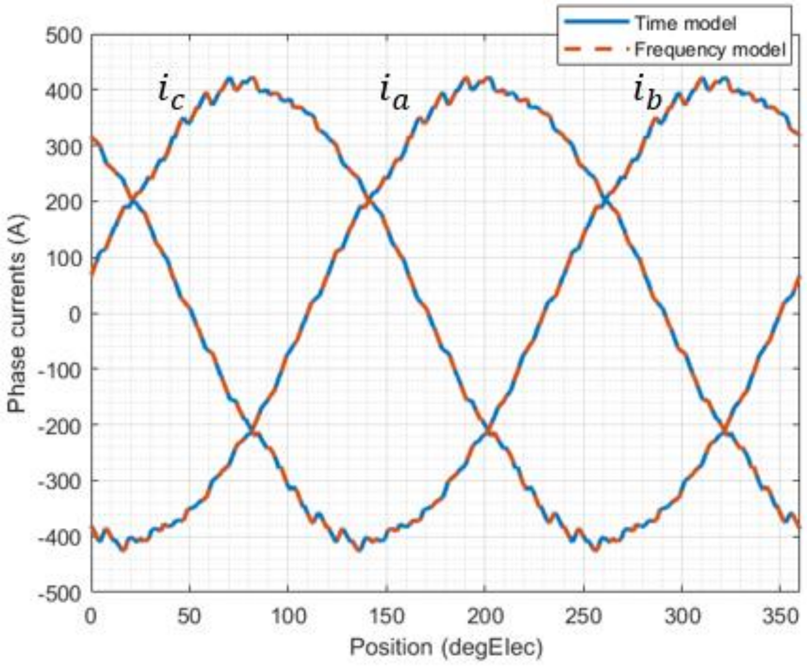
RESULTS – MOTOR CURRENTS COMPUTATION

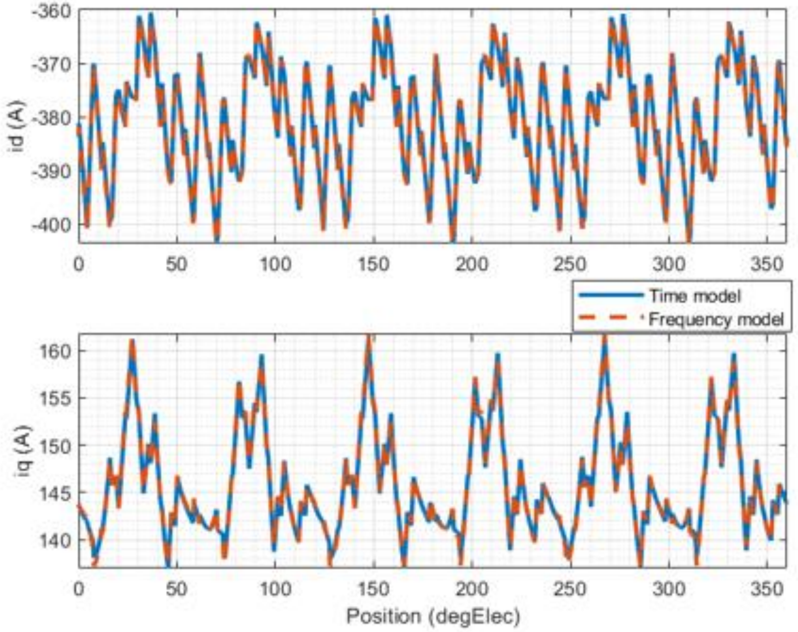
Sustainable mobility

Comparison: frequency-based model vs time-based model

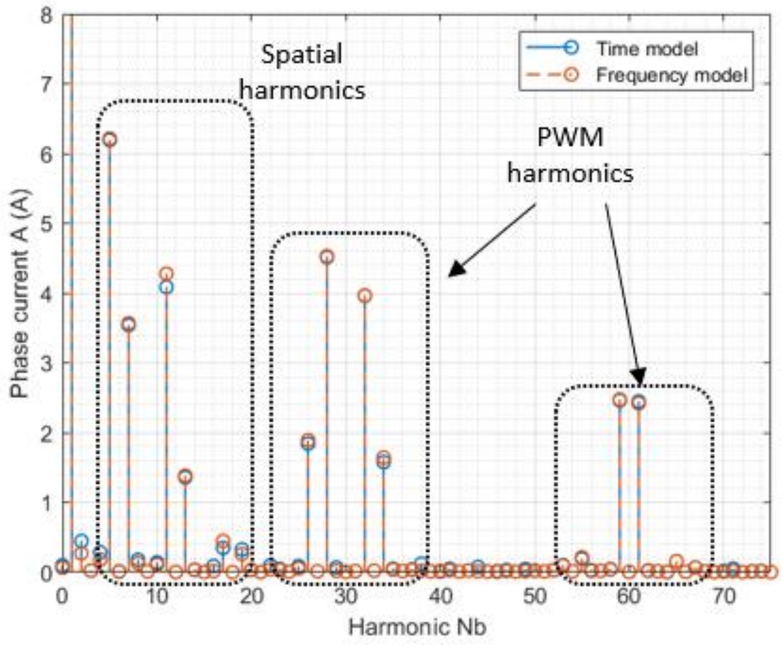
→ Results are identical. Frequency-based model is perfect for steady-state study



Phase currents



D-Q currents



Fourier transform (I_a)

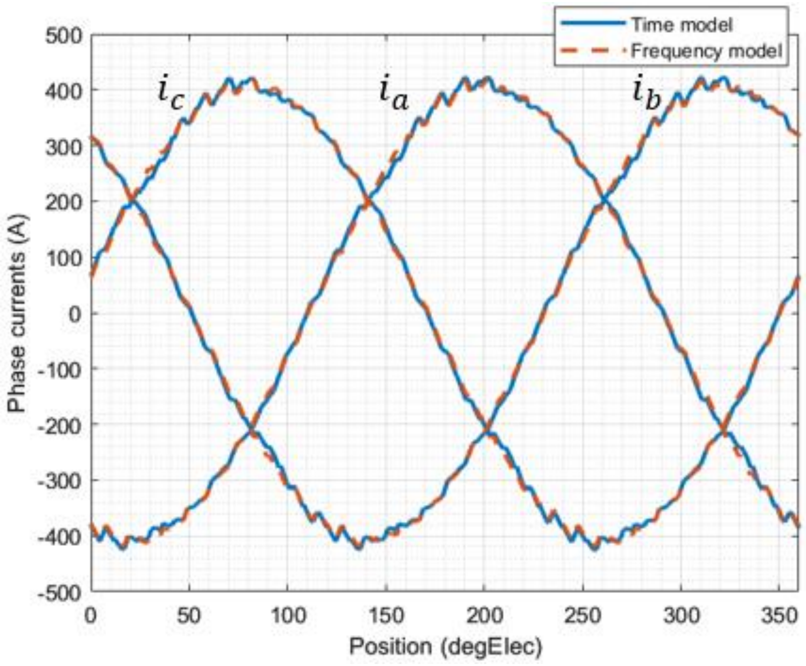
RESULTS – MOTOR CURRENTS COMPUTATION

Sustainable mobility

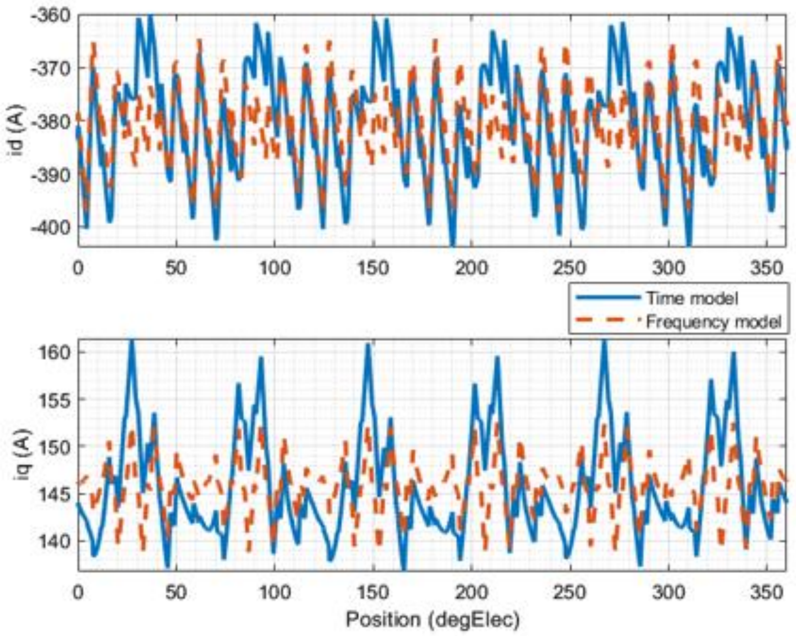
Comparison: frequency-based model vs time-based model

→ Results are identical. Frequency-based model is perfect for steady-state study

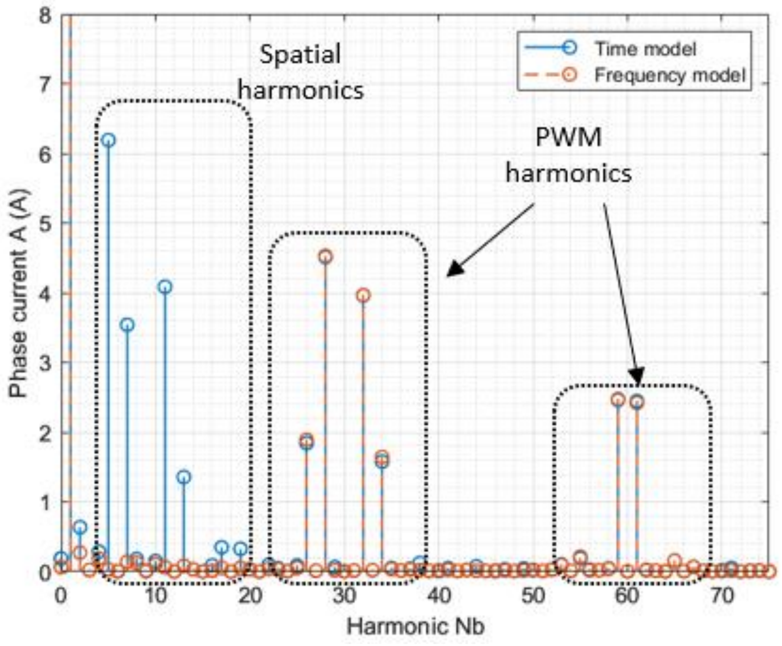
→ **Without space harmonics** included in the frequency-based model: a significant difference



Phase currents



D-Q currents

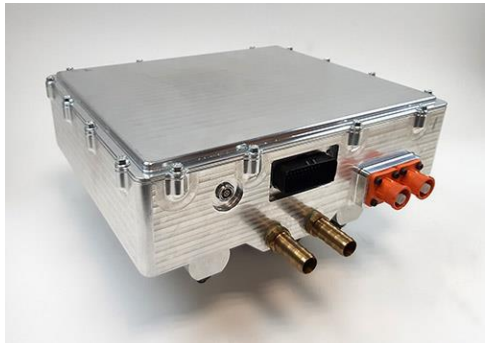


Fourier transform (I_a)

RESULTS – MOTOR CURRENTS COMPUTATION

Sustainable mobility

Methodology: Experimental validation setup



200kW Inverter SiC + CTRL

150 kW Motor

Test bench

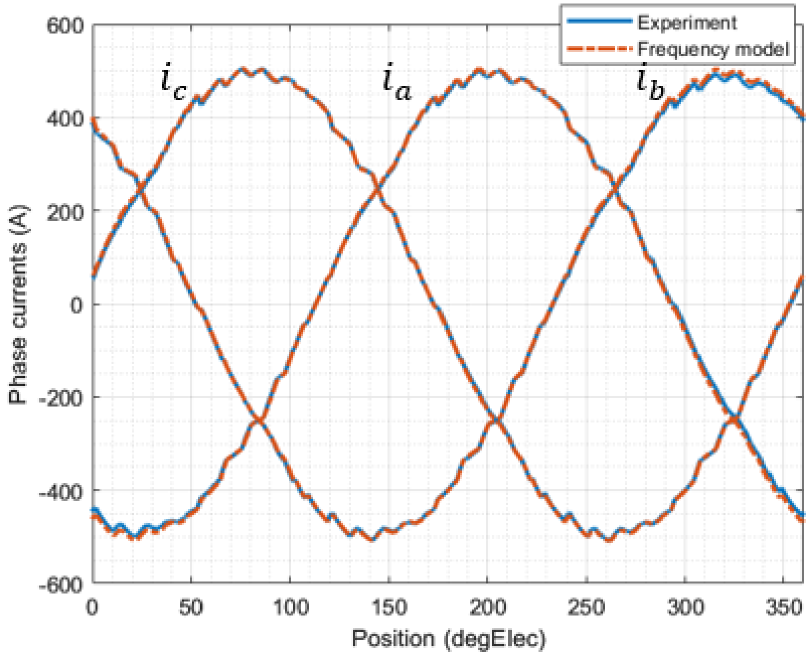
RESULTS – MOTOR CURRENTS COMPUTATION

Sustainable mobility

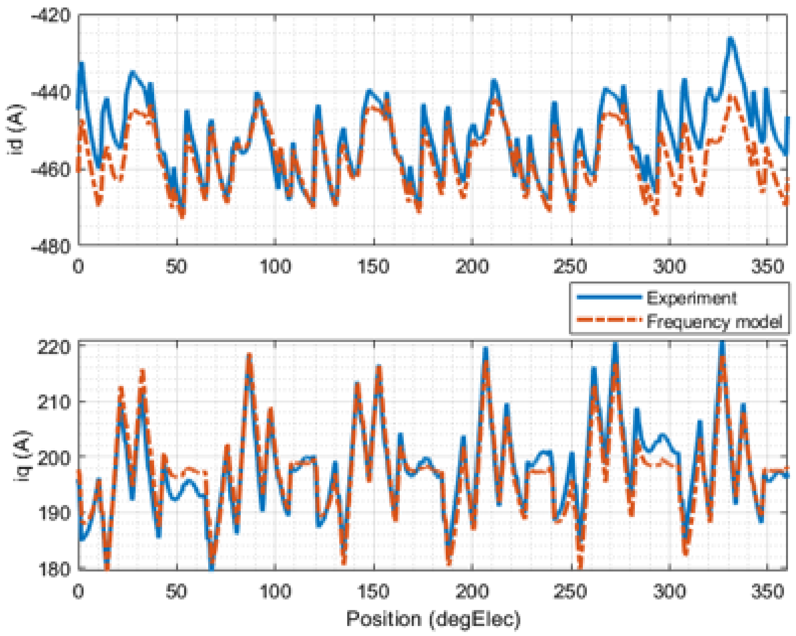
Comparison: frequency-based model vs experiment

→ Results are very accurate

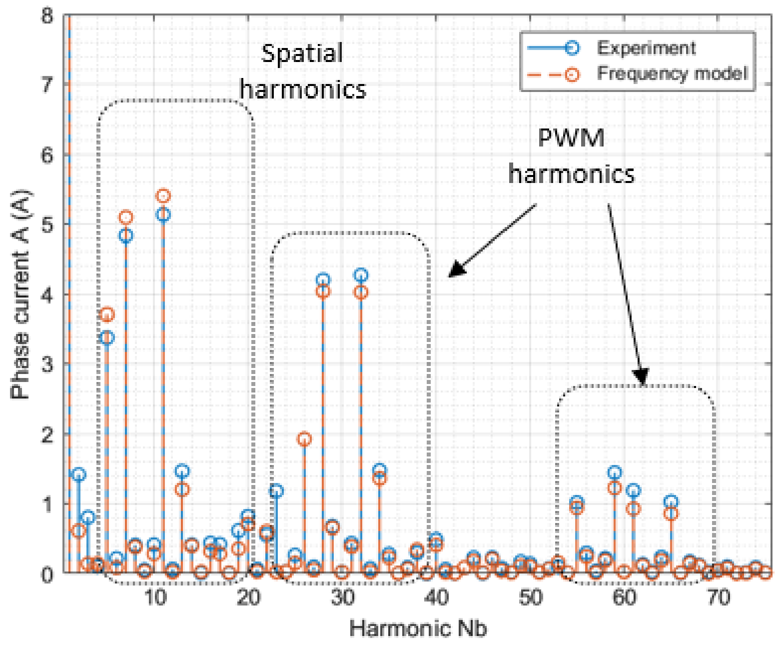
→ Slight discrepancies occur, mostly due to dynamic current control



Phase currents



D-Q currents



Fourier transform (I_a)

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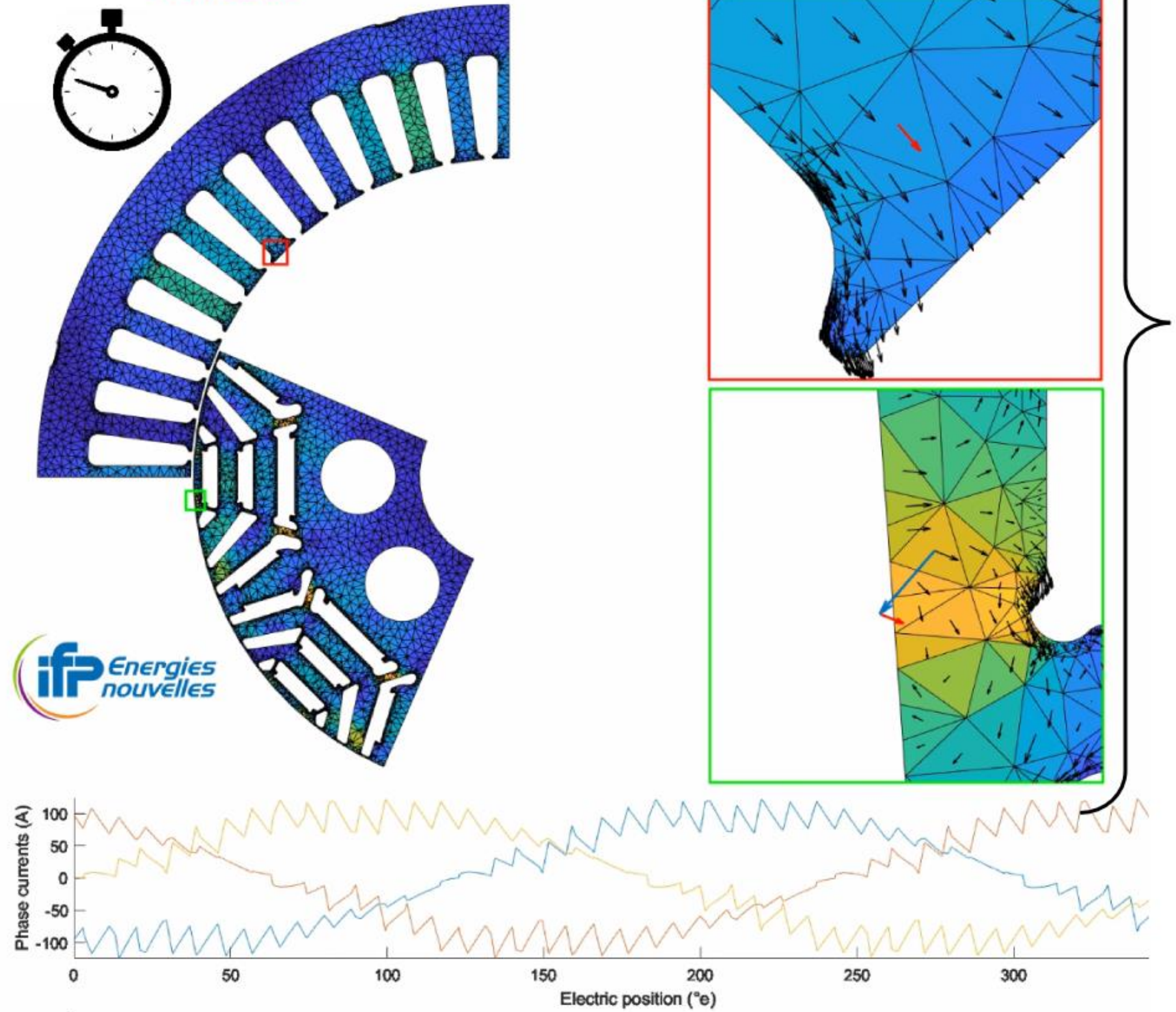
RESULTS – MOTOR LOSSES COMPUTATION

Iron Losses - Finite Elements

>1 hour



Methodology: traditional losses computation

→ Fields are computed in each mesh

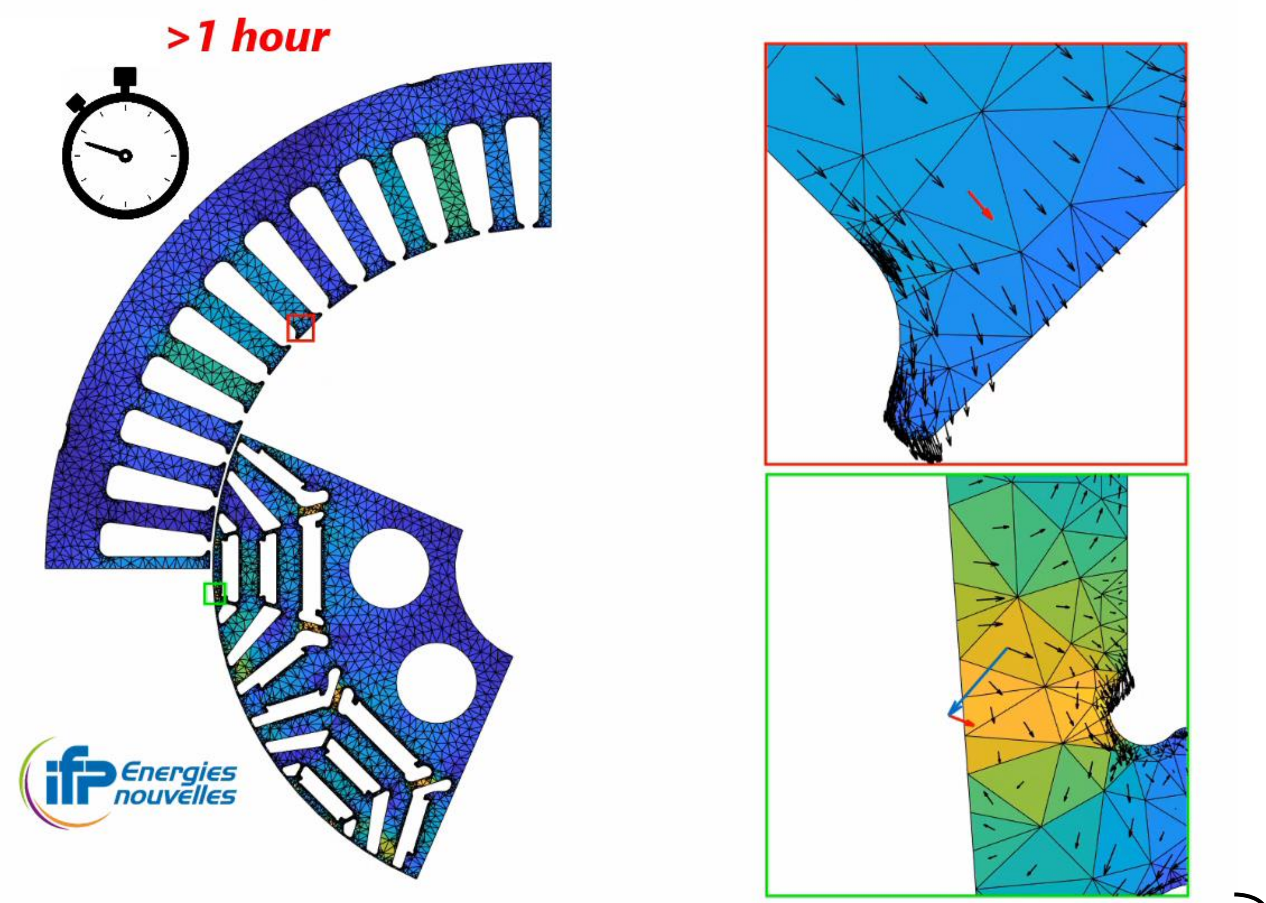
→ A losses formula is then applied, for example a modified frequential Bertotti:

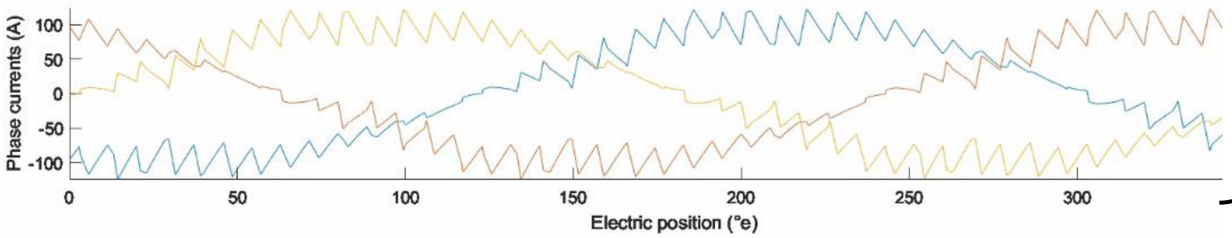
$$P_{loss} = K_{hyst}(f)\widehat{B}^2 f + K_{eddy}(f)\widehat{B}^2 f^2 + K_{exc}(f)\widehat{B}^{1.5} f^{1.5}$$

RESULTS – MOTOR LOSSES COMPUTATION

Sustainable mobility

Iron Losses - Finite Elements





Methodology: **traditional losses computation**

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Methodology: **phase current frequencies model**

→ Identification of an equivalent resistance

→ R_{eq} is a generic function of f_h:

$$P_{loss} = \sum_{h=0}^{\infty} R_{eq}(f_h)\, I_h^2$$

0.1 sec

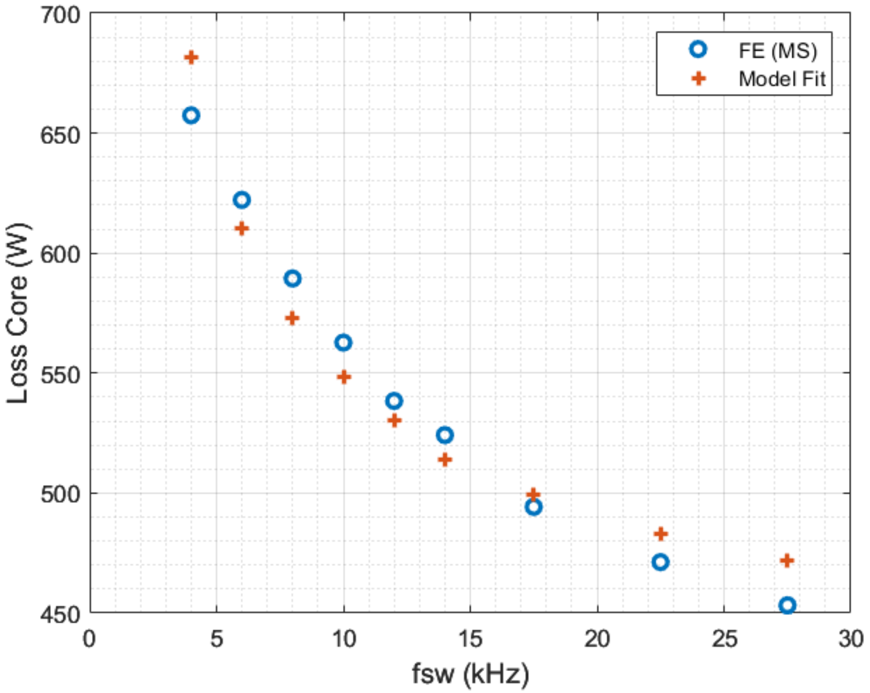
RESULTS – MOTOR LOSSES COMPUTATION

Sustainable mobility

Comparison: R_{eq} model vs FE model

→ Results are obtained for a switching frequency sweep with SVPWM control

→ Global trend is correctly identified. However, correlation is not as good for highest switching frequencies



Motor iron losses vs switching frequency

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RESULTS – MOTOR LOSSES COMPUTATION

Sustainable mobility

Comparison: R_{eq} model vs FE model

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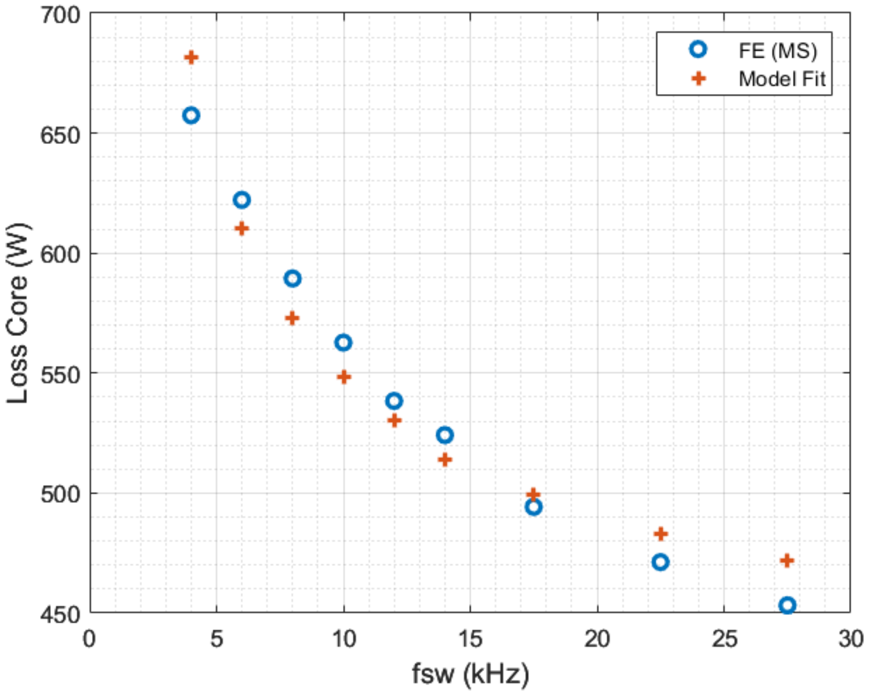
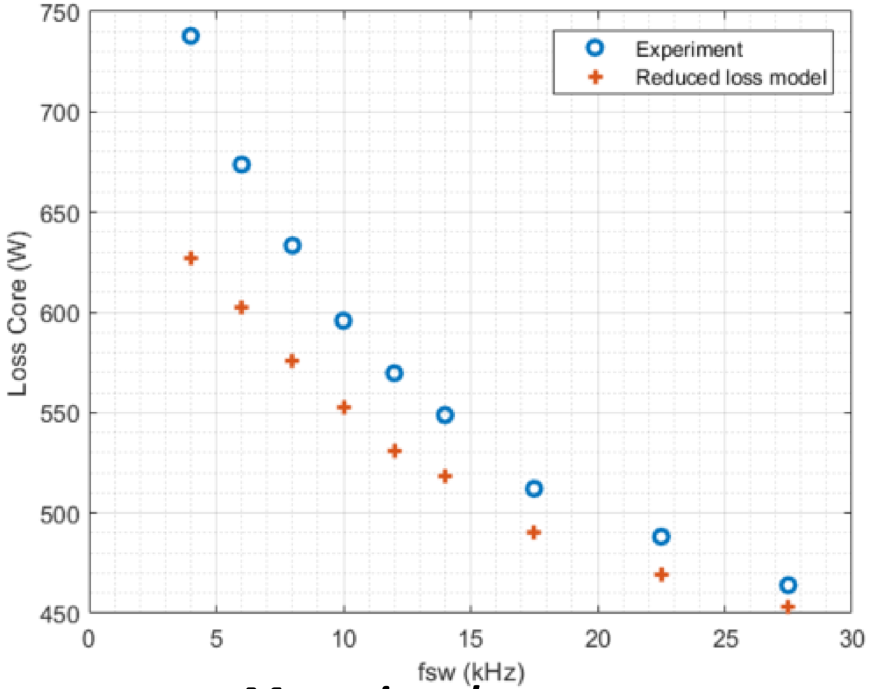


Motor iron losses vs switching frequency

Comparison: R_{eq} model vs experiment

→ Significant differences were observed but are of 100W maximum

→ Global trend is only roughly identified. <u>This is the consequence of the source FE model</u>



Motor iron losses vs switching frequency

RESULTS – MOTOR LOSSES COMPUTATION

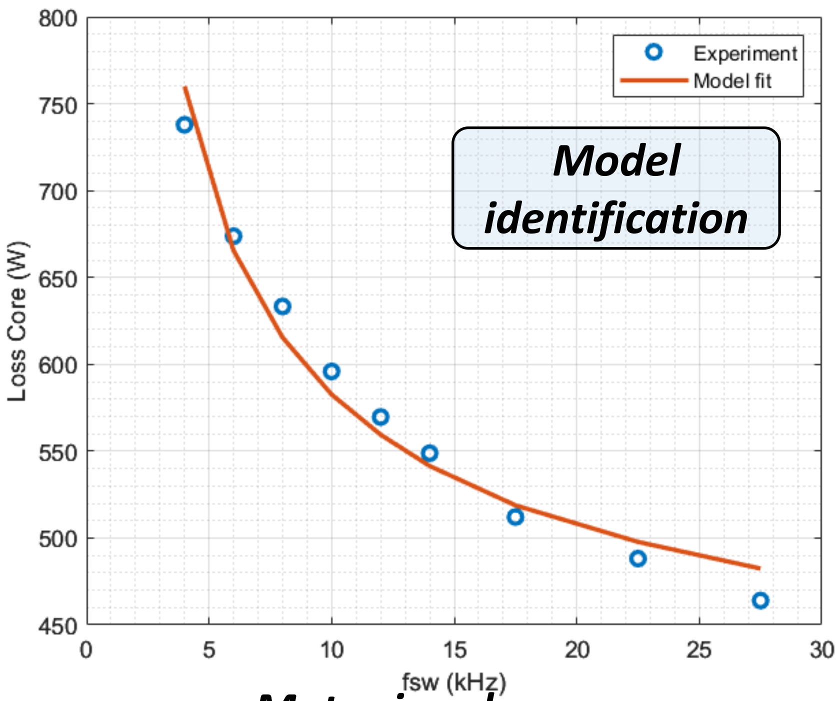
Sustainable mobility

Comparison: Recalibrated R_{eq} model vs experiment

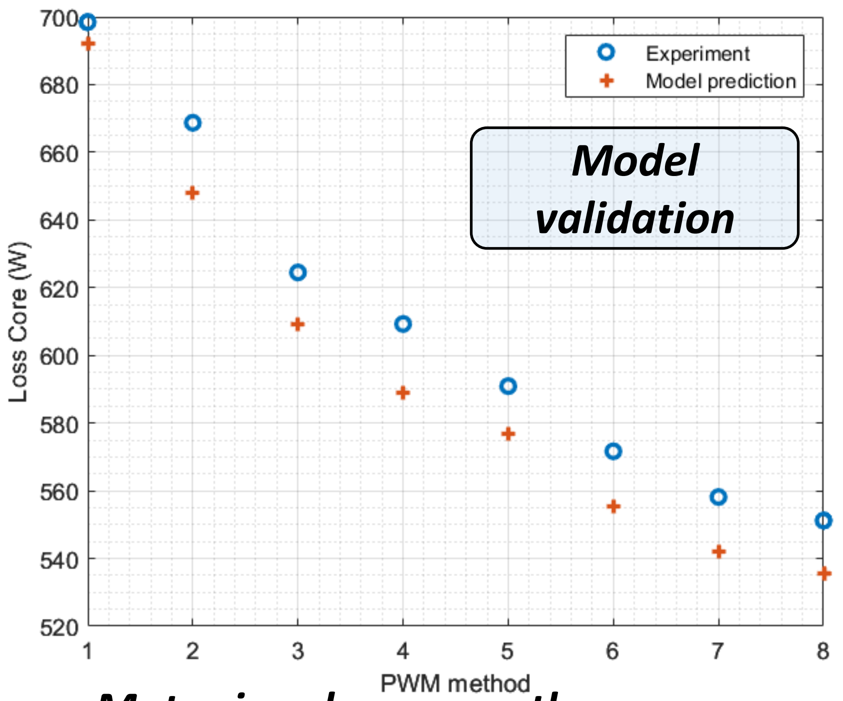
→ The simplicity of the reduced model was leveraged to **directly identify the model from experimental** frequency sweep with SVPWM

→ Global trend is again correctly identified.

→ Model was then validated using results obtained with other types of modulations



Motor iron losses vs switching frequency



Motor iron losses vs other PWM modulations

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RESULTS – MOTOR LOSSES COMPUTATION

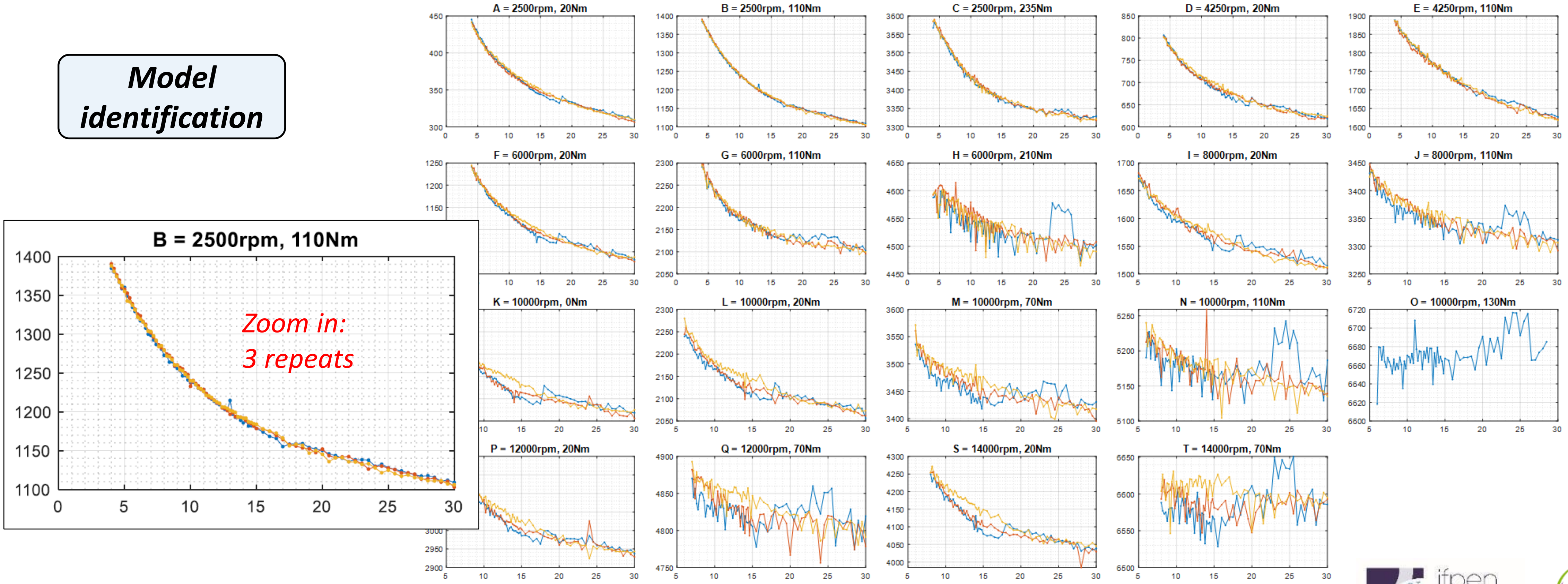
Sustainable mobility

Comparison: Recalibrated R_{eq} model vs experiment

→ The simplicity of the reduced model was leveraged to **directly identify the model from experimental** frequency sweep with SVPWM

→ Done on several operating points

Model identification



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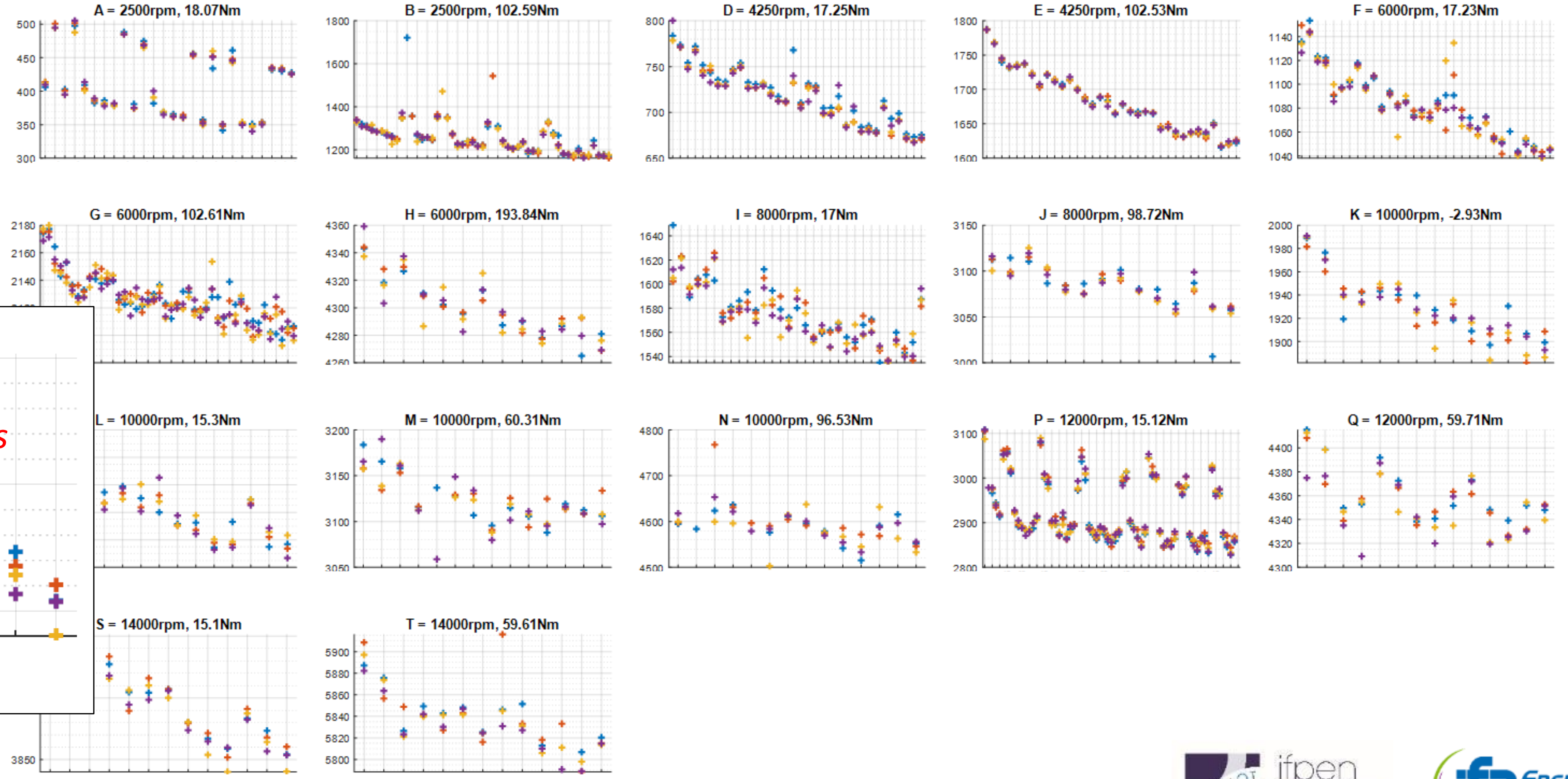
RESULTS – MOTOR LOSSES COMPUTATION

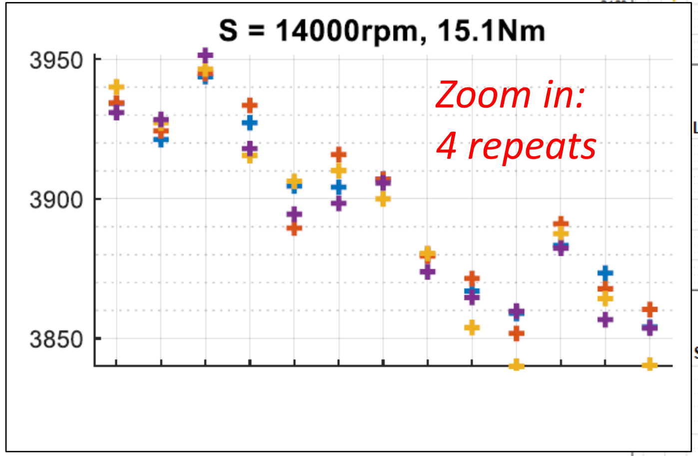
Comparison: Recalibrated R_{eq} model vs experiment

→ The simplicity of the reduced model was leveraged to **directly identify the model from experimental** frequency sweep with SVPWM

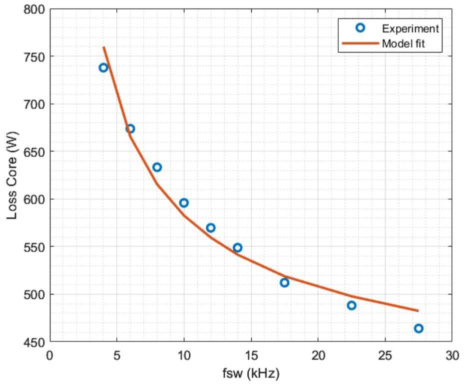
→ Done on several operating points

Model validation





RESULTS – MOTOR LOSSES COMPUTATION

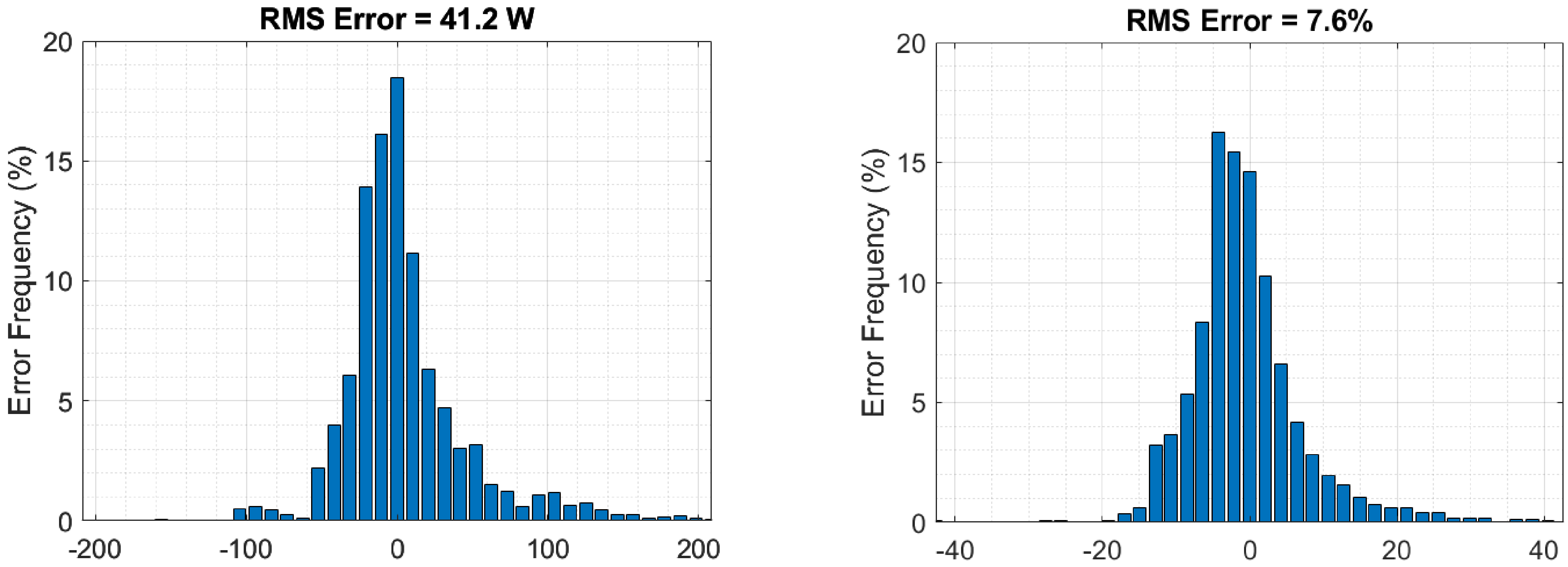


Sustainable mobility

Comparison: Recalibrated R_{eq} model vs experiment

→ Under 8% of relative mean error

→ Under 50W of absolute mean error



Motor losses model performance

SUMMARY

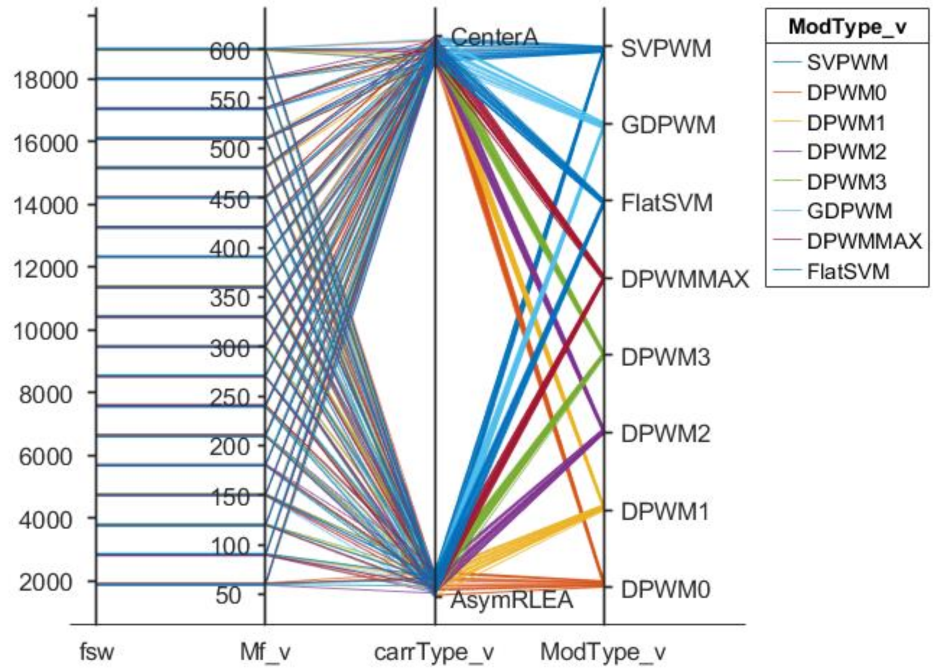
Sustainable mobility

Sustainable mobility

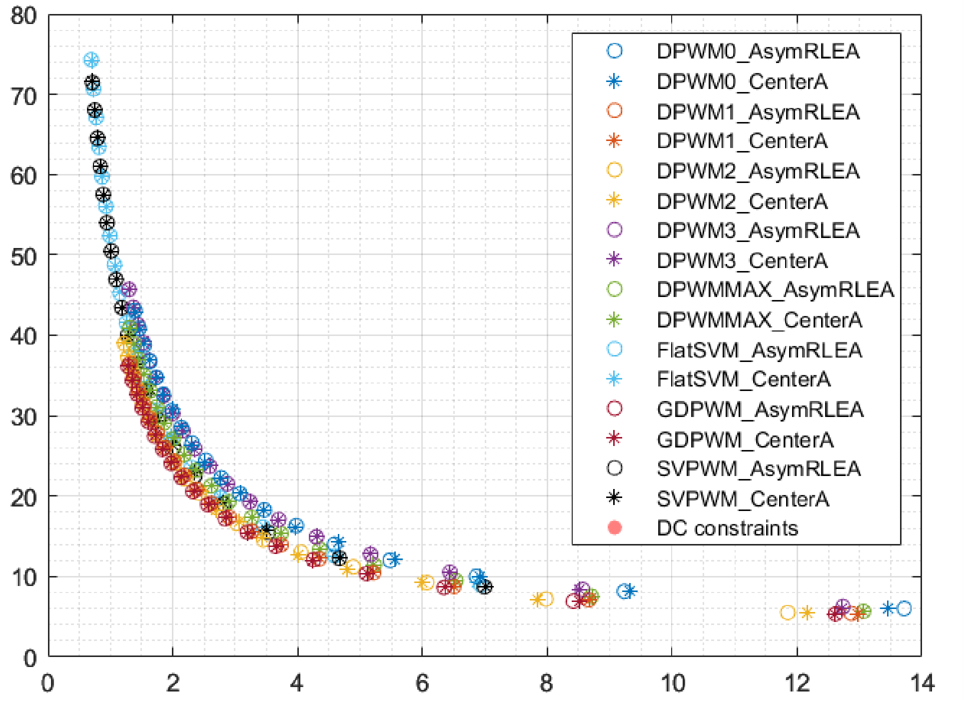
Optimization process

→ We now will use our fast computing model to evaluate a great number of PWM configuration efficiently (~50000 schemes/hour)

→ Data analysis can provide insight, but the development of adaptable KPI for automatic choice is key



PWM schemes evaluated



Results

CONCLUSION

Sustainable mobility

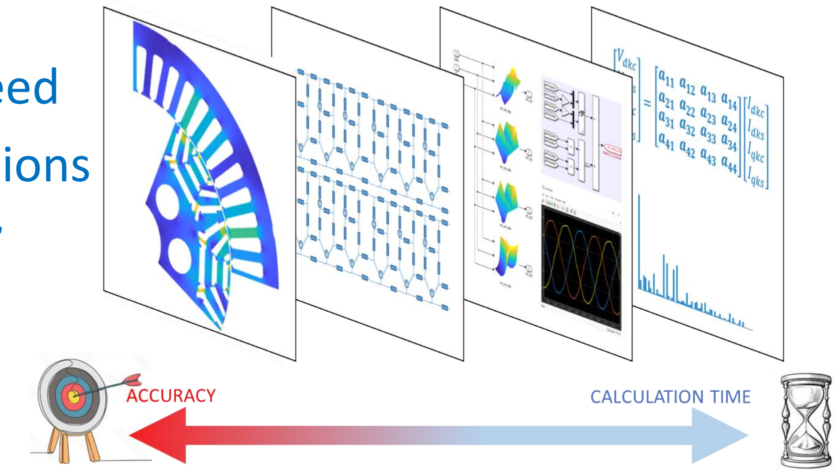
- Model reduction is a key approach for improving hardware and software solutions
  - For example, setting up PWM control offers endless choices
  - Everything cannot be evaluated on a test bench
  - Simulation computations are often too time-consuming or too inaccurate

- IFPEN implemented a method for improved simulation accuracy and speed

→Combining results from finite elements simulations and analytical equations into **frequency-based models**, currents, flux, including space harmonics, as well as motor losses can be **computed x1000 times faster**

→The reduced model can also be used to improve the FE model regarding losses computation

→Simulation can now be used to optimize motor controls



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