«EMR-based PMSM Scaling Laws for Electric Vehicles»

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- Outline -

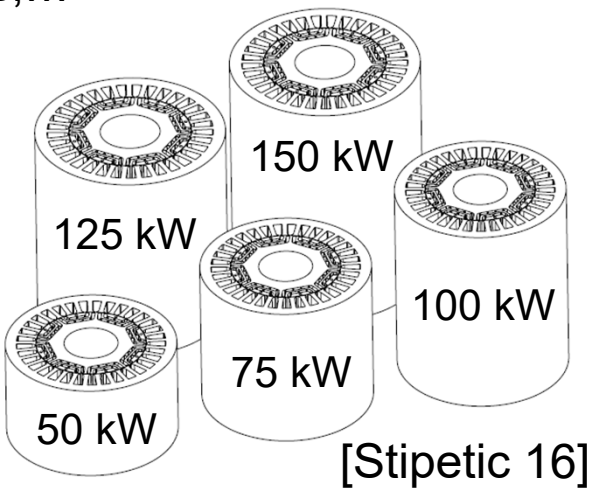
1 **Scaling laws of electric machines**

2 **EMR-based scaling laws**

3 **Application case**

reference: https://www.renaultgroup.com

- ❑ Wide range of automotive applications
- ❑ Different requirements, power ratings dimensions,…



[Stipetic 16]

- ❑ A growing interest in the scalability of electric machines to meet market requirements

❖ **Objective:**

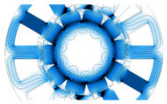
Develop a method supporting the scalability of electric machines for system-level investigations (energy consumption assessment, optimization, etc)

EMR-based PMSM Scaling Laws for Electric Vehicles

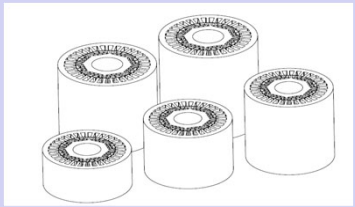
- Different granularity of models for designing electric machines -

Accuracy / Level of details
Number of parameters

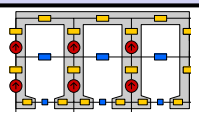
/!\ Repeat for each every change of requirements



Numerical models
FEM

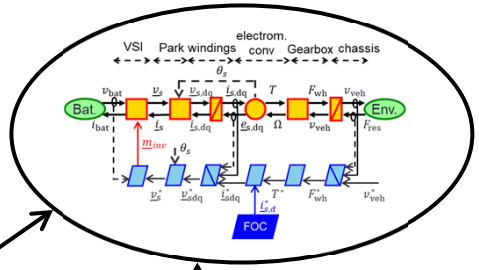


Sizing,
Electromagnetic design,
investigation of specific phenomena

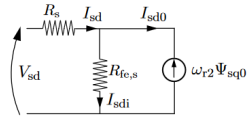


Semi-analytical models
MEC

Vehicle model



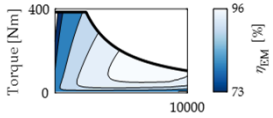
Data



Analytical models

Behavior modeling,
component control laws

Energy management strategies development

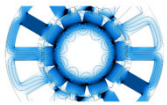


Mapping-based models

Fast computation-time/System-level compatibility

EMR-based PMSM Scaling Laws for Electric Vehicles

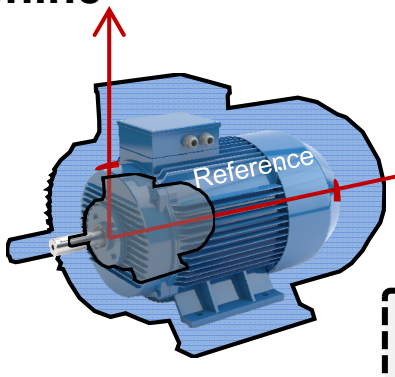
- Scaling laws: a solution to accelerate the design process -



Numerical models
FEM

Data of 1 reference machine

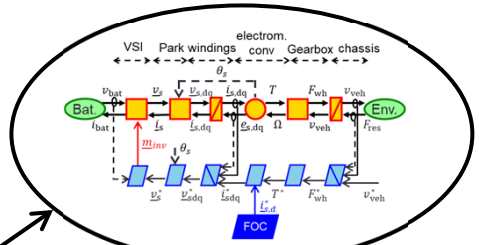
Scaling laws

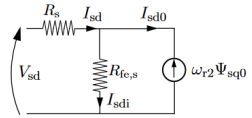


Scaled Data

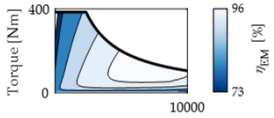
Distinct geometries
Different power rating

Vehicle model



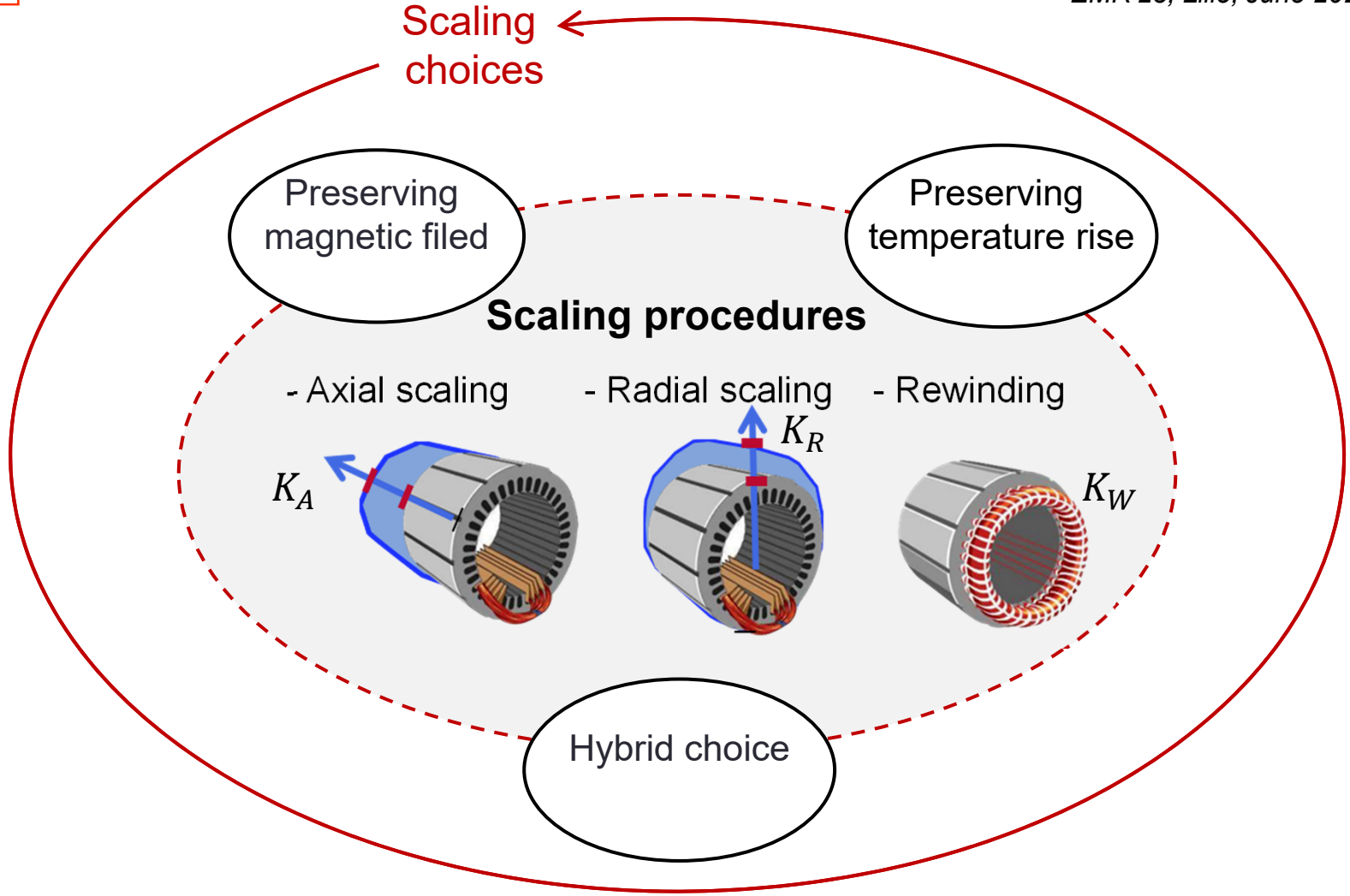


Analytical models



Mapping-based models

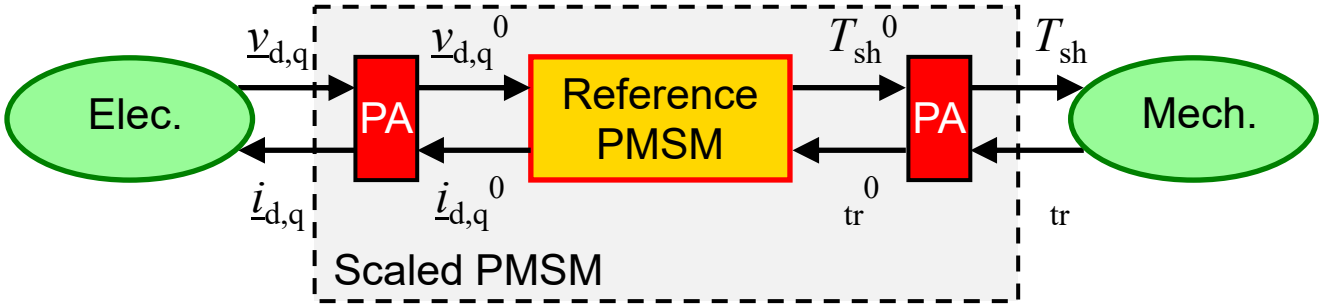
- Different choices for the scaling process -



The derivation of the scaling laws depends on the scaling choice

« EMR-based scaling laws»

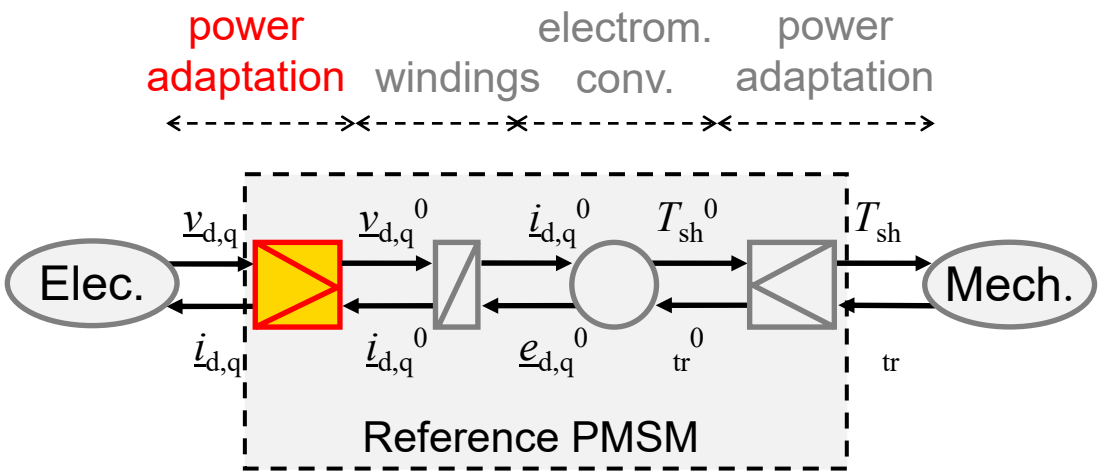
➢ Organization of the scalable model following EMR rules, but with a new approach



- Fixed model of the reference machine accompanied with two power adaptation elements (PA)
- Only manipulation of inputs and outputs of the reference model
- Easy reuse of the model

[Lhomme 20]

- Derivation of the electric power adaptation element -

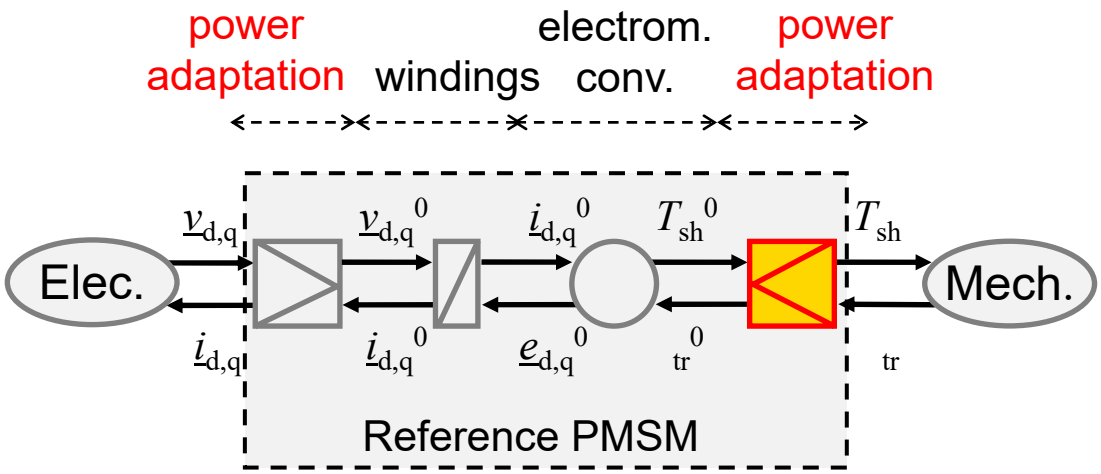


$$\begin{cases} \underline{v}^{0}_{d,q} & \left(\underline{v}_{d,q}/K_v\right) - \Delta R^{0}\underline{i}^{0}_{d,q} \\ \underline{i}_{d,q} & K_i\underline{i}^{0}_{d,q} \end{cases}$$

$$\begin{cases} \text{Voltage scaling factor } K_v & K_A K_R^{\mathbf{n}} K_W \\ \text{Current scaling factor } K_i & \dfrac{K_R^{\mathbf{m}}}{K_W} \\ \text{Equivalent resistor} \Delta R^{0} & \dfrac{1}{K_R^{x}}\left(\dfrac{R^{0}_{co}}{K_R} + \dfrac{R^{0}_{ew}}{K_A}\right) - R^{0} \end{cases}$$

The superscripts n, m, and x depend on the scaling choice

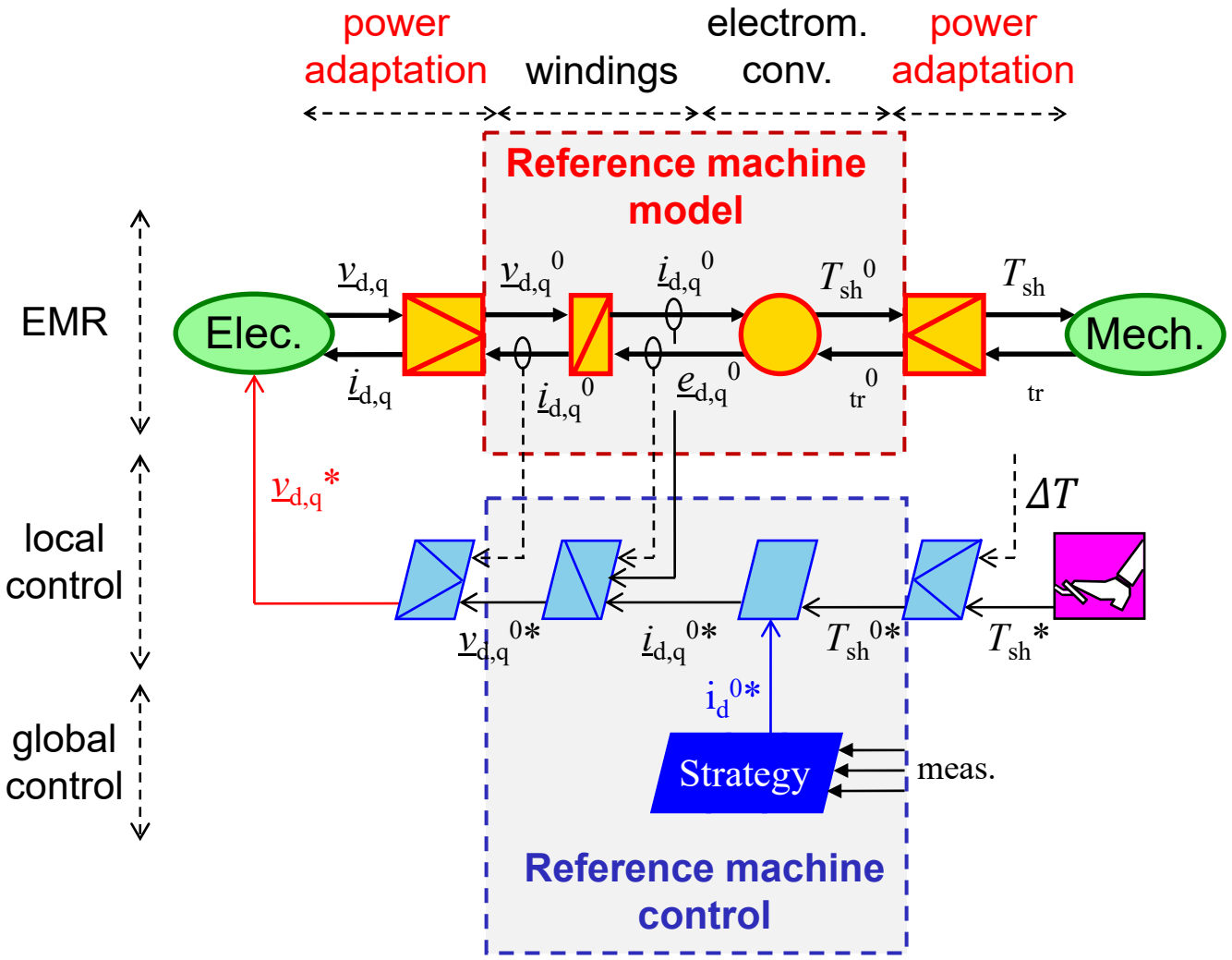
- Derivation of the mechanical power adaptation element -



$$\begin{cases} \text{Torque scaling factor } K_T & K_A K_R^{\alpha} \\ \text{Equivalent iron loss} \Delta T_{fer} & K_T\left(\frac{1}{K_R^{\beta}} - 1\right) T_{fer}^{0} \\ \text{Equivalent PM loss} \Delta T_{PM} & K_T\left(K_R^{\gamma} - 1\right) T_{PM}^{0} \end{cases}$$

$$\begin{cases} T'_{sh} & K_T T_{sh}^{0} - \Delta T \\ \Delta T & \Delta T_{fer} + \Delta T_{PM} \\ \Omega & \Omega^{0} \end{cases}$$

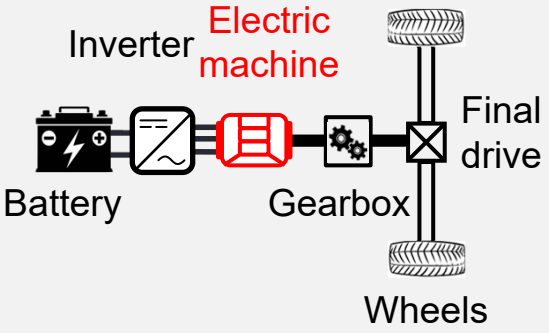
The superscripts , , and depend on the scaling choice


power adaptation
windings
electrom. conv.
power adaptation
Reference machine model
EMR
local control
global control
Elec.
Mech.
Strategy
meas.
ΔT
Reference machine control

« Application case »

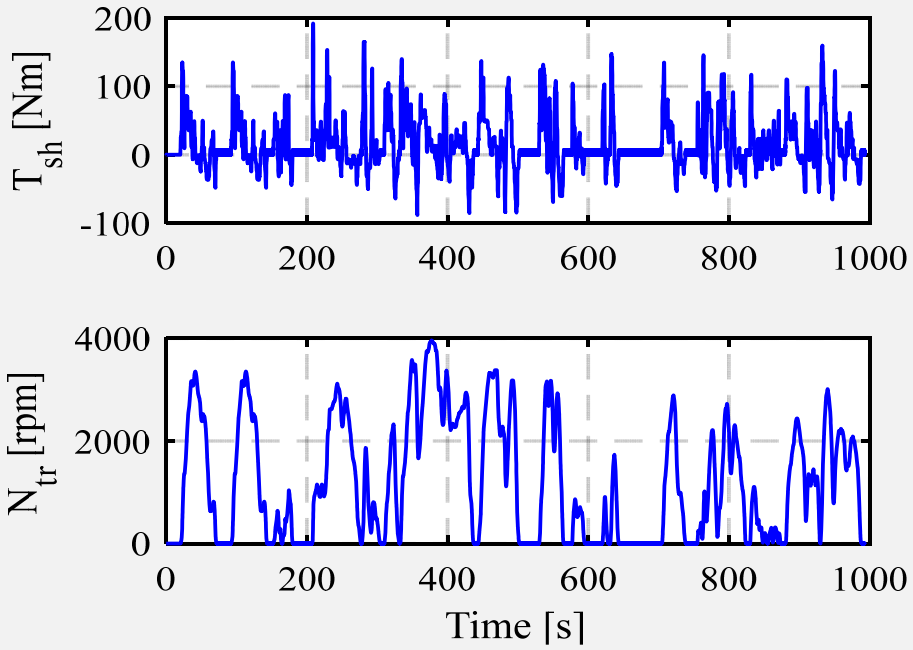
- Application case for electric vehicle -

80 kW



Sportive version
Enhanced acceleration through **power scaling** by a factor of **1.375**
➔ **110 kW**

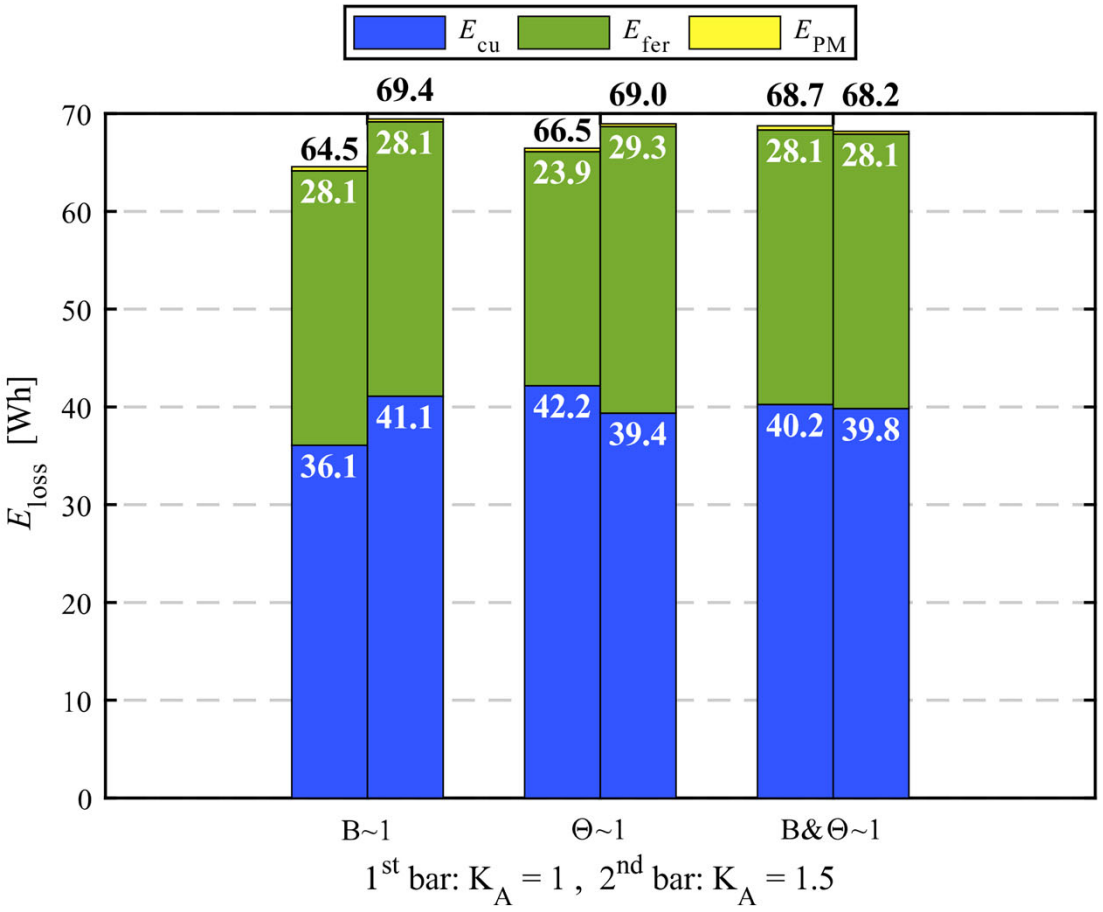
Application of the method to analyze the influence of scaling choices on power loss distribution



Artemis Urban driving cycle

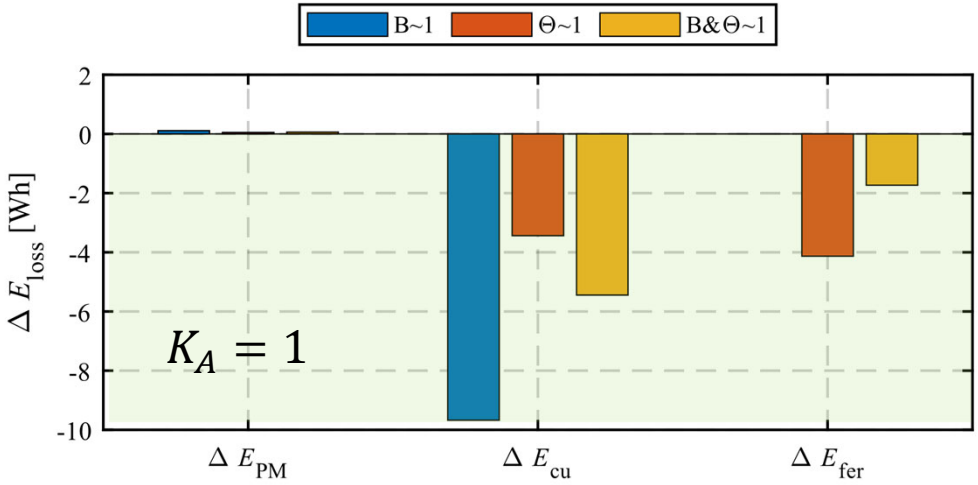
- Results of the simulation-

Two investigated scaled design with different axial and radial scaling factors

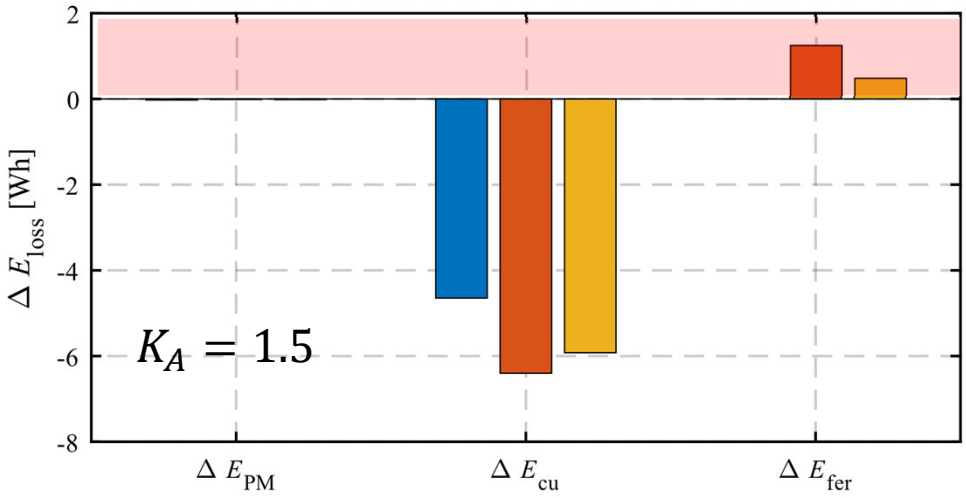


- A few-Wh difference resulting from various scaling choices is insignificant for both the machine and the vehicle

- Analysis of the losses inside the power adaptation elements -



Negative values = lower losses as compared to the reference design



Positive values = higher losses as compared to the reference design

« Conclusion »

- Summing up -

- EMR-based scaling laws allows:
  - Model reuse (reference model + two power adaptation elements)
  - Control reuse of the reference machine
  - Test of several machine designs with different power ratings, distinct geometries
- No significant impact on the scaling choices for the studied case
- Perspectives:
  - EMR-based scaling laws for other components (inverter, gearbox…)

[Aroua 21]: A. Aroua, W. Lhomme, F. Verbelen, A. Bouscayrol, K. Stockman, "Inversion-based Control of Scaled PMSM for Battery Electric Vehicles "2021 IEEE Vehicle Power and Propulsion Conference (VPPC), Gijón, Spain, Oct. 2021

[Lhomme 20]: W. Lhomme, F. Verbelen, M. N. Ibrahim, and K. Stockman, "Energetic Macroscopic Representation of Scalable PMSM for Electric Vehicles ", in *2020 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Gijon, Spain, Nov. 2020, p. 1-6. doi: 10.1109/VPPC49601.2020.9330981

[Stipetic 16]: S. Stipetic, D. Zarko, and M. Popescu, "Ultra-fast axial and radial scaling of synchronous permanent magnet machines ", *IET Electr. Power Appl.*, vol. 10, nº 7, p. 658-666, Aug. 2016, doi: 10.1049/iet-epa.2016.0014