« EMR-based Control of a Multi-drive System for Aeronautic »

Le Tam PHAM, **Ngac Ky NGUYEN**

L2EP, ENSAM, France

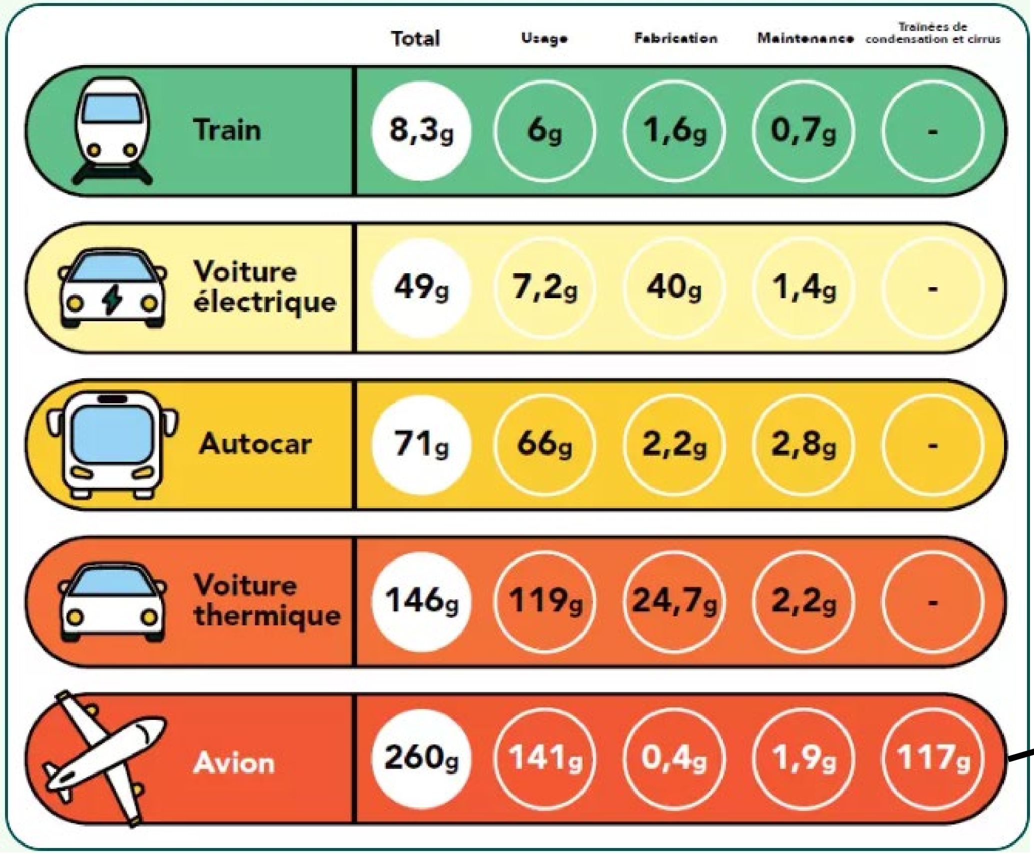
Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Arts et Métiers Sciences et Technologies

« 1. More Electric Aircraft »

Carbon comparator for different modes of transport (gCO2e/Passenger/Kilometer)

(SNCF 2025)



	Total	Usage	Fabrication	Maintenance	Traînées de condensation et cirrus
Train	8,3g	6g	1,6g	0,7g	-
Voiture électrique	49g	7,2g	40g	1,4g	-
Autocar	71g	66g	2,2g	2,8g	-
Voiture thermique	146g	119g	24,7g	2,2g	-
Avion	260g	141g	0,4g	1,9g	117g

Higher power density
Lower torque ripple
Having fault tolerance

Multiphase Drive

Three-phase drive

- Limitation of on-board energy
- Fault-Intolerant (sensor, electronic devices, windings…)

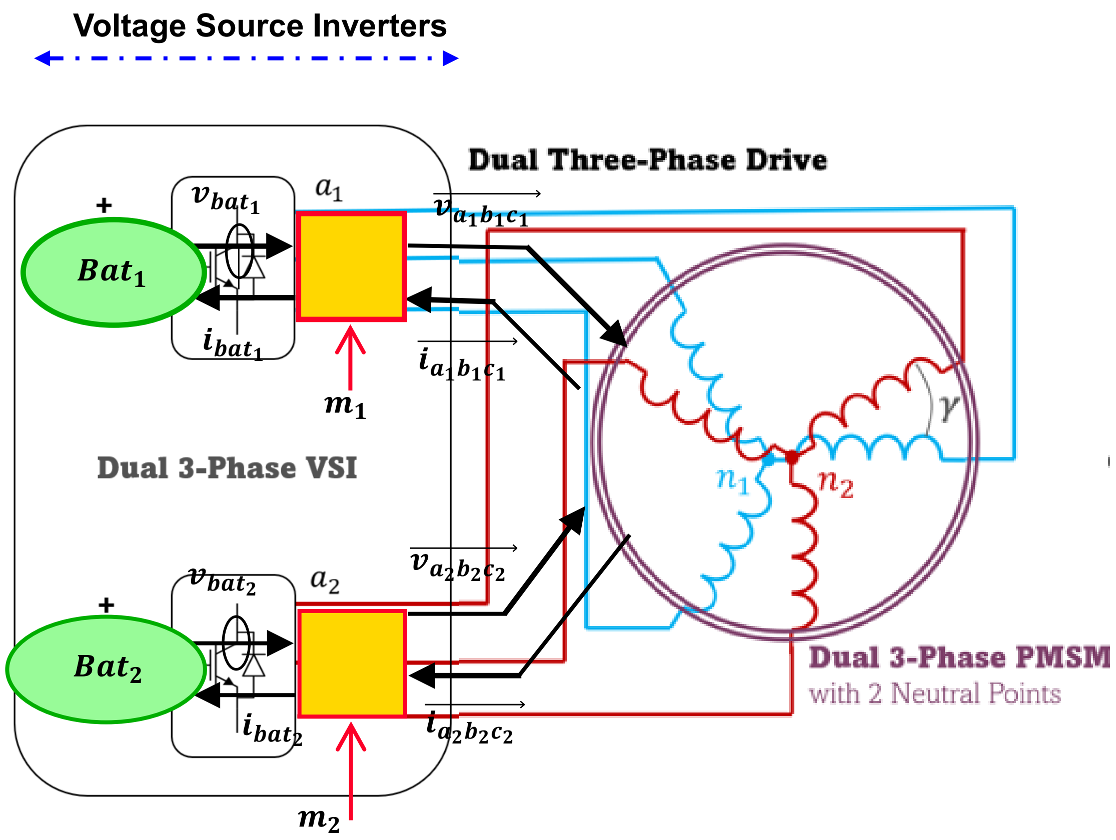
More electric aircraft

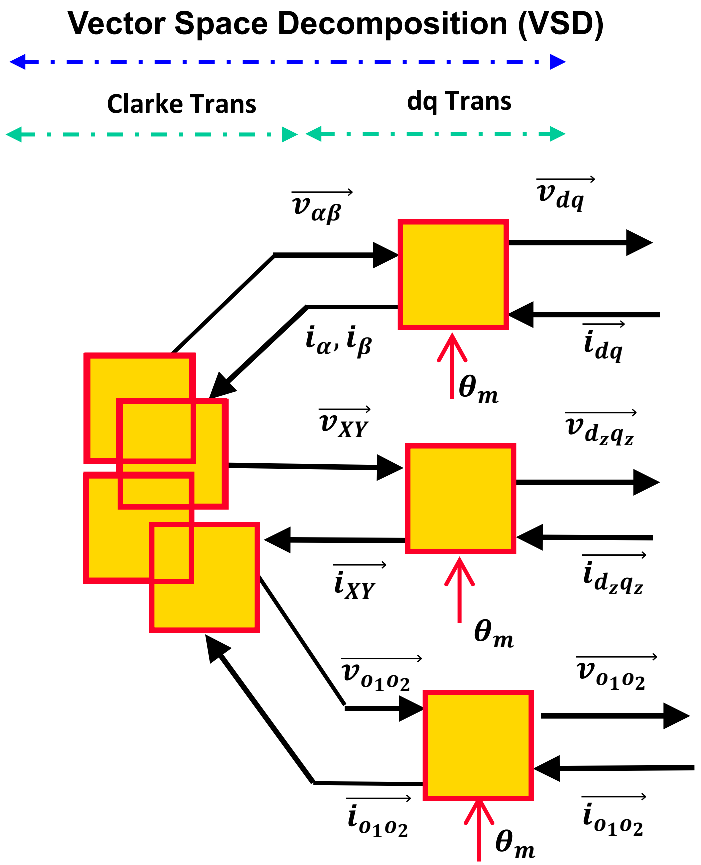
Urban Air Mobility

CityAirbus NextGen

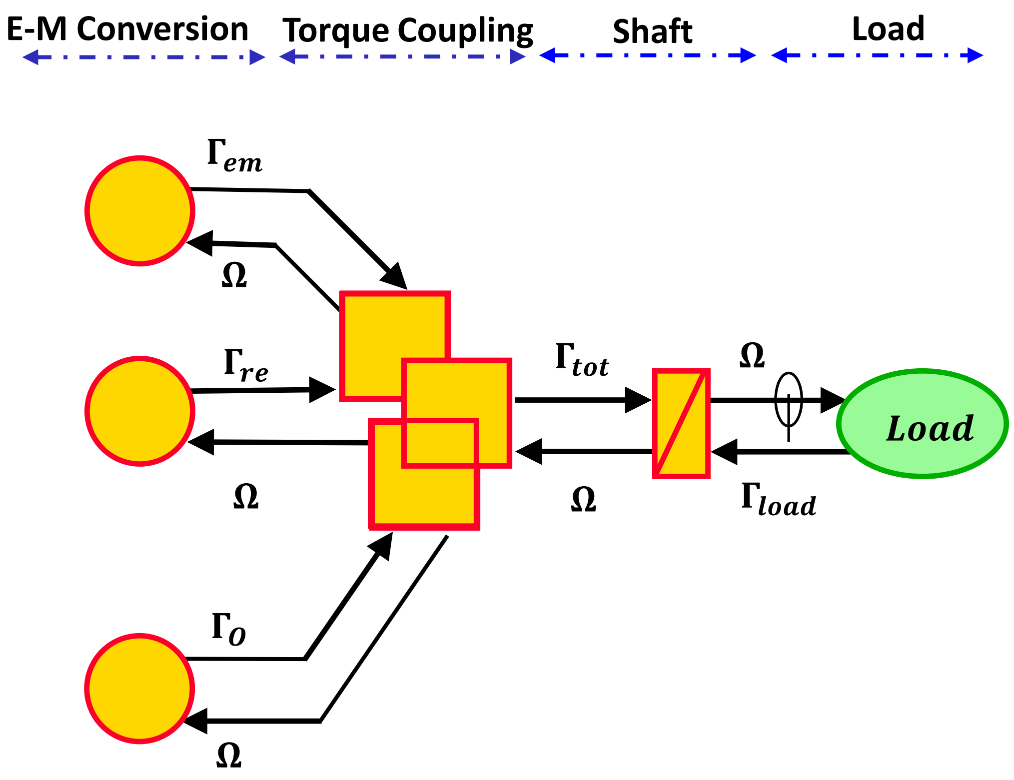
« 2. EMR-based Model of Dual 3-Phase Drive considering Iron Loss »

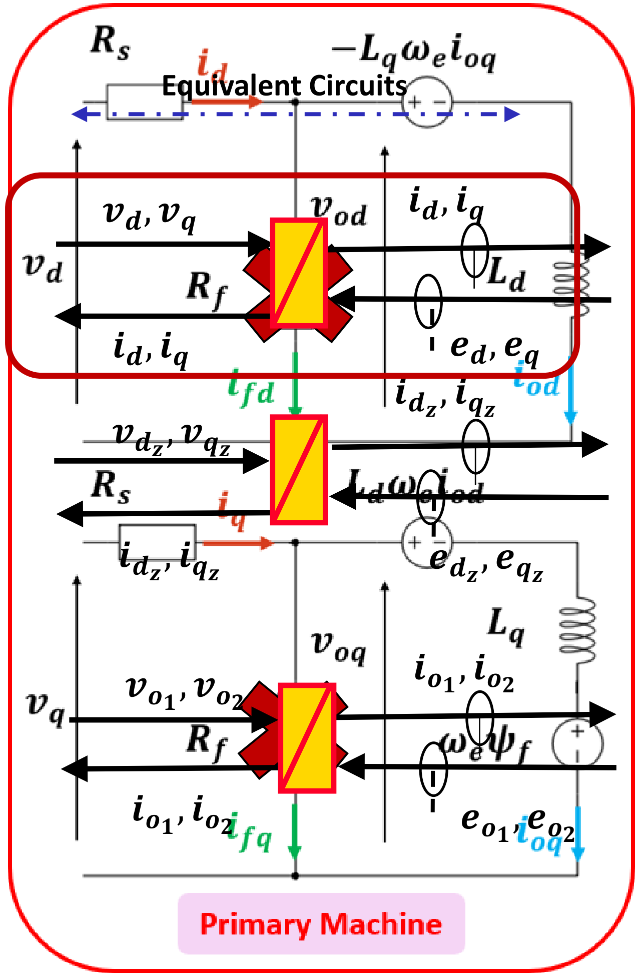
2.1 Vector Space Decomposition





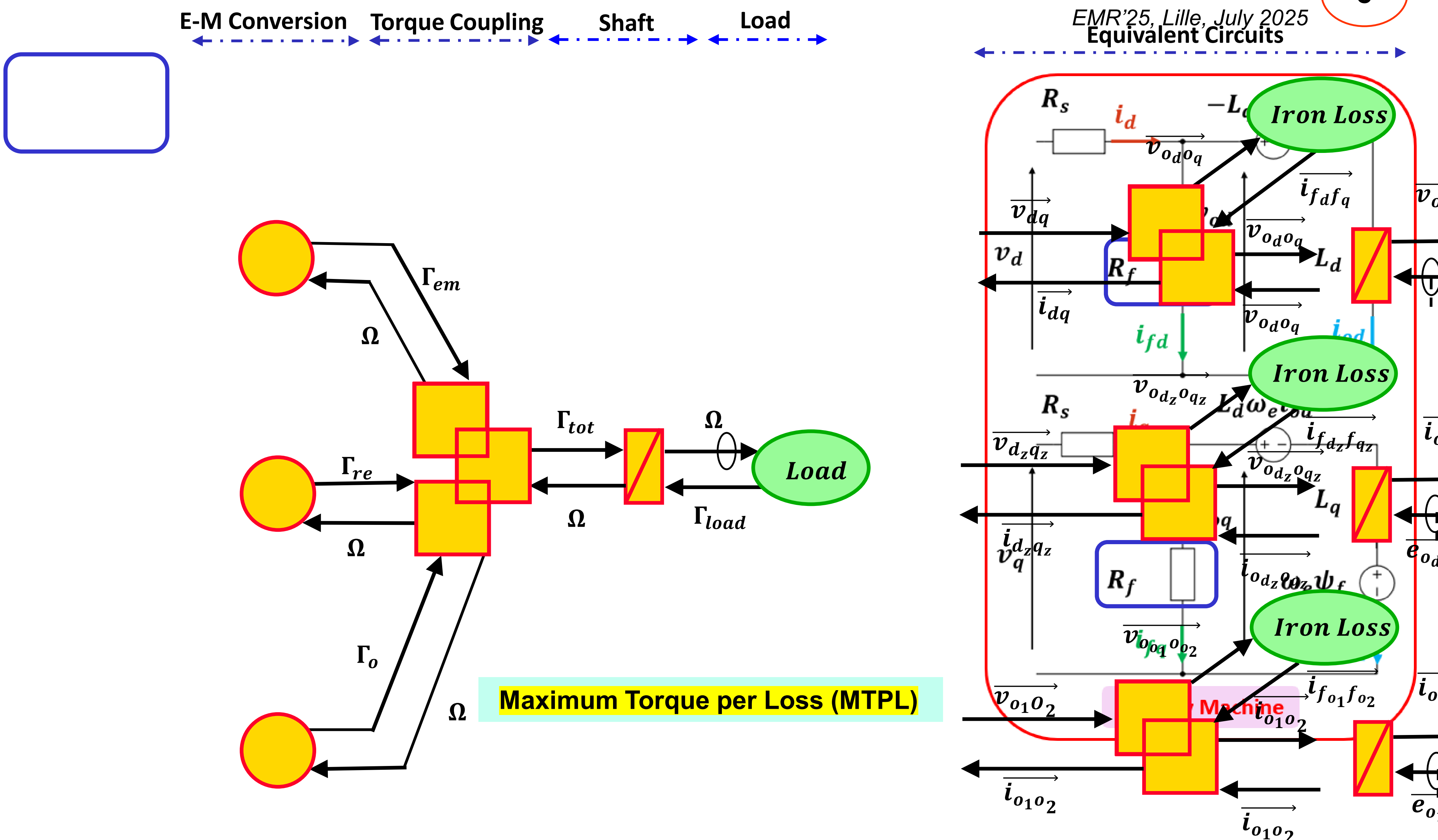
Modelling without considering Iron Loss → Maximum Torque per Ampère (MTPA)





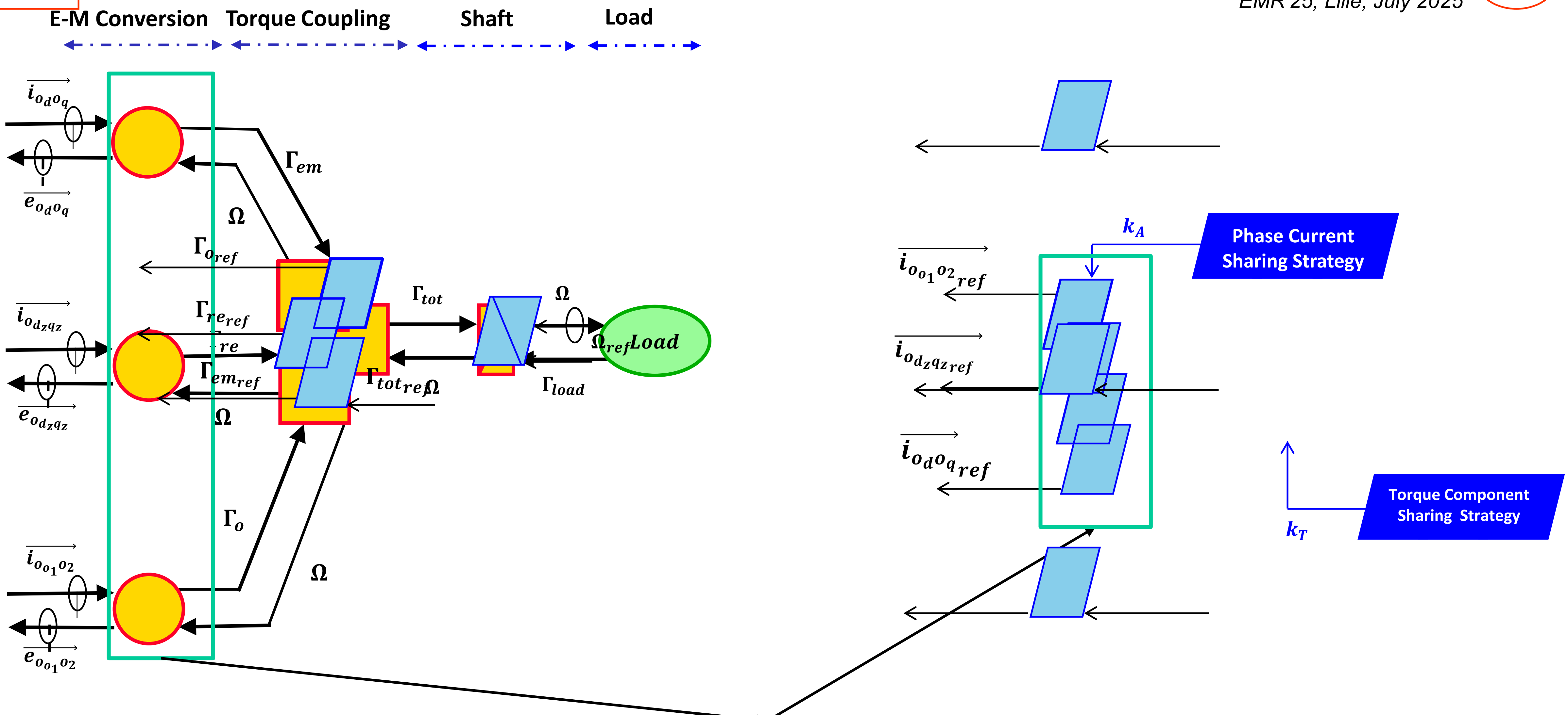
Similarity for equivalent circuit of other fictious machines

2.2 System Modelling considering Iron Loss



« 3. Inversion-based Control with Maximum Torque Distribution per Loss »

3.1 General Strategies

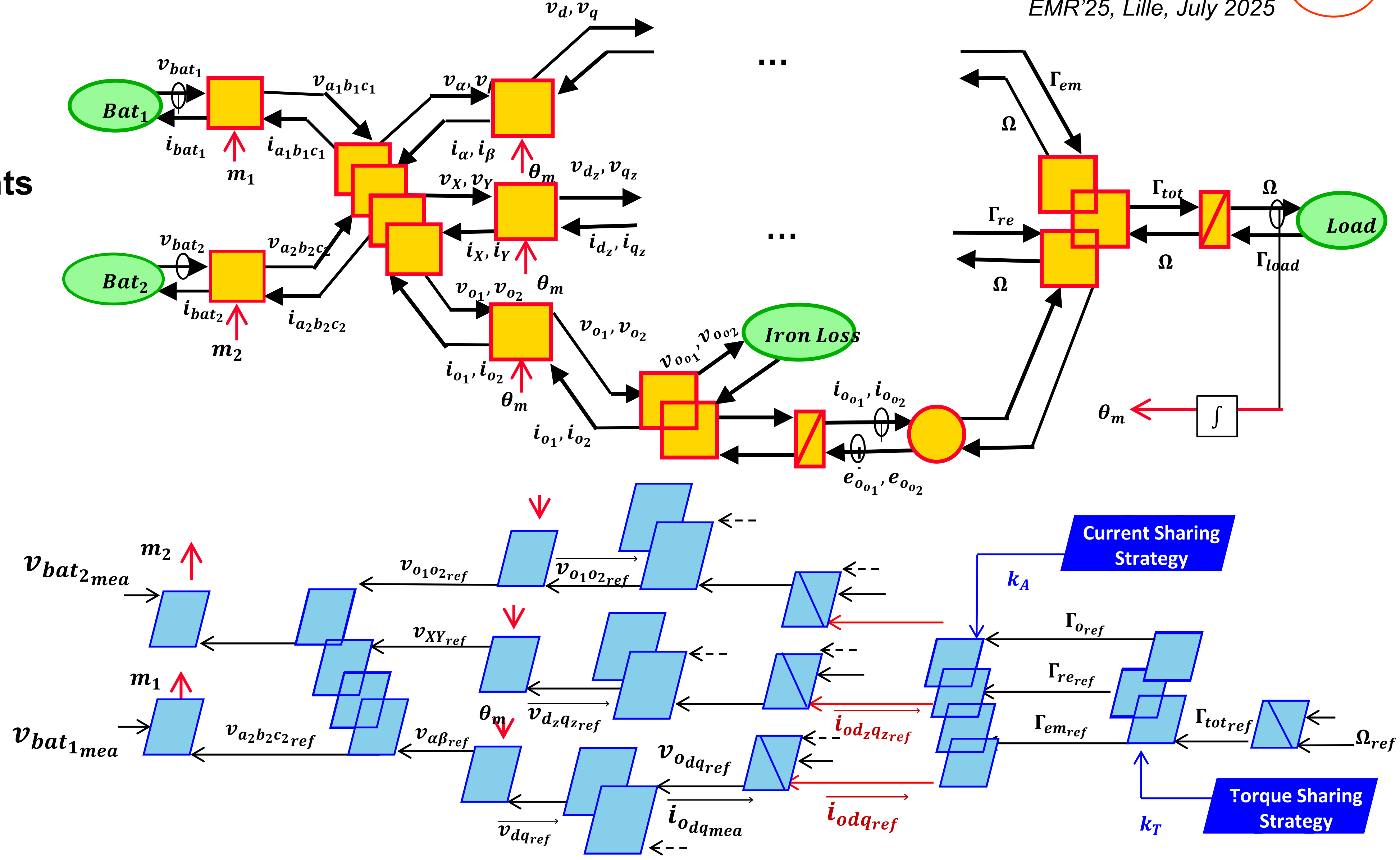


Based on the relationship between $\overrightarrow{i_{dq}}, \overrightarrow{i_{d_z q_z}}$ with phase currents $\overrightarrow{i_{a_1 b_1 c_1}}, \overrightarrow{i_{a_2 b_2 c_2}}$

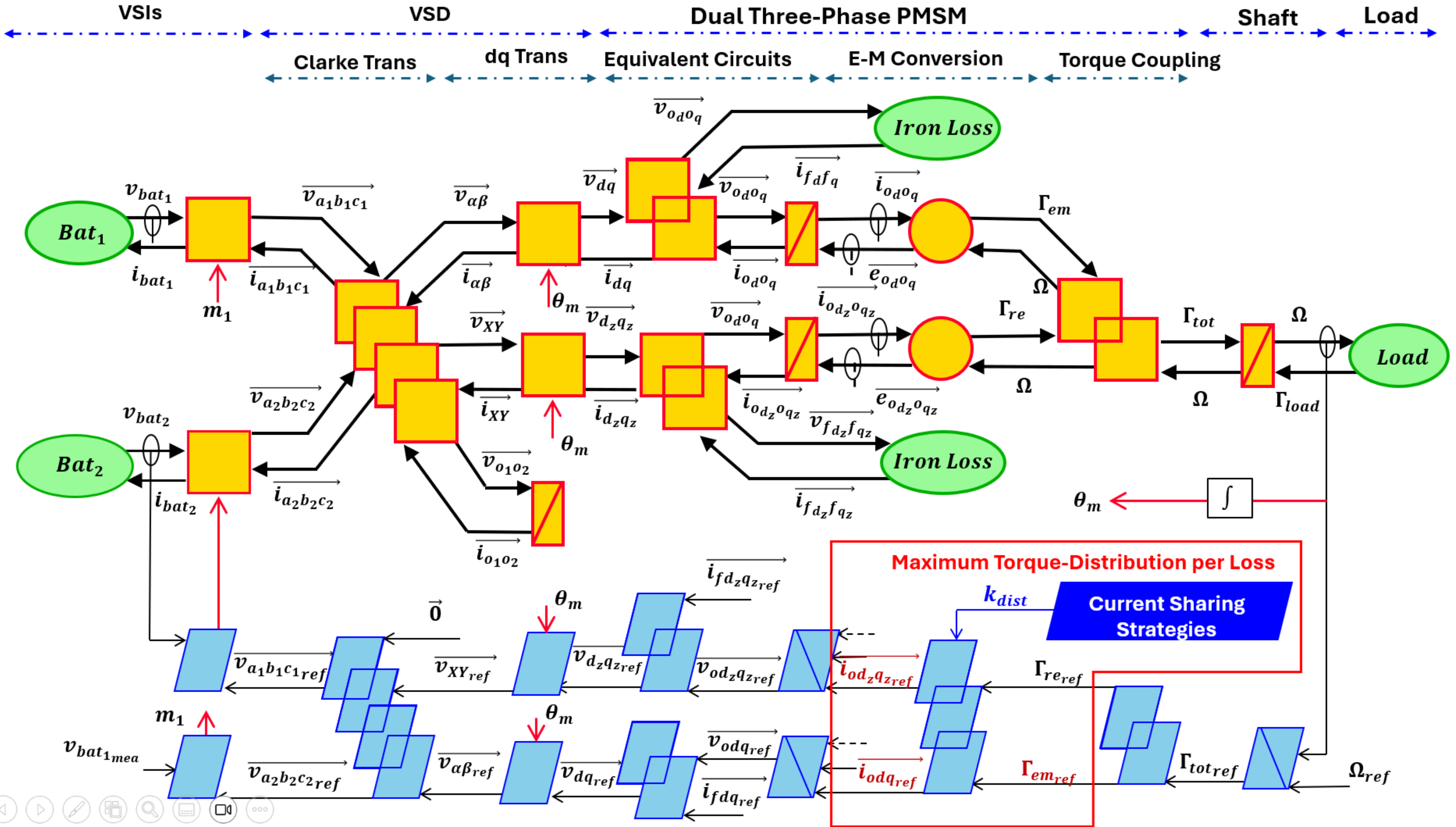
3.2 Specific case: Surface-mounted PMSM

Two isolated neutral points
$\rightarrow i_{o_1} = i_{o_2} = 0$

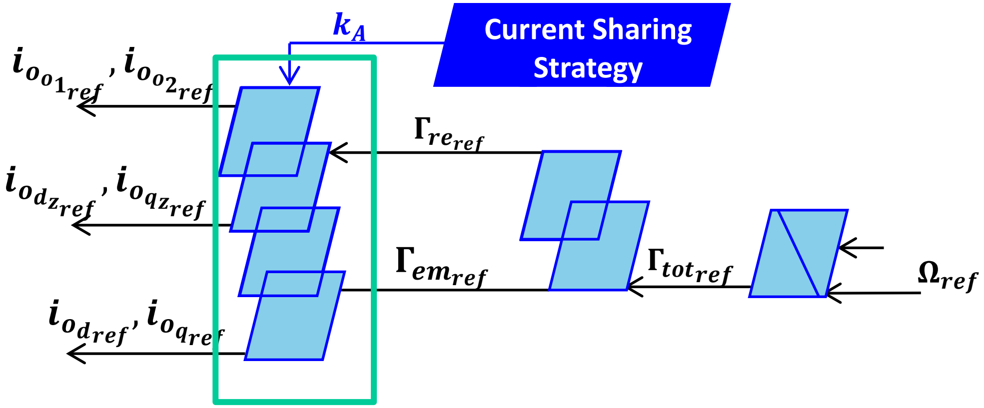
Surface-Mounted PMSM
$\rightarrow \Gamma_{re} = 0$



3.2 Specific case: Surface-mounted PMSM



3.2 Maximum Torque Distribution per Loss

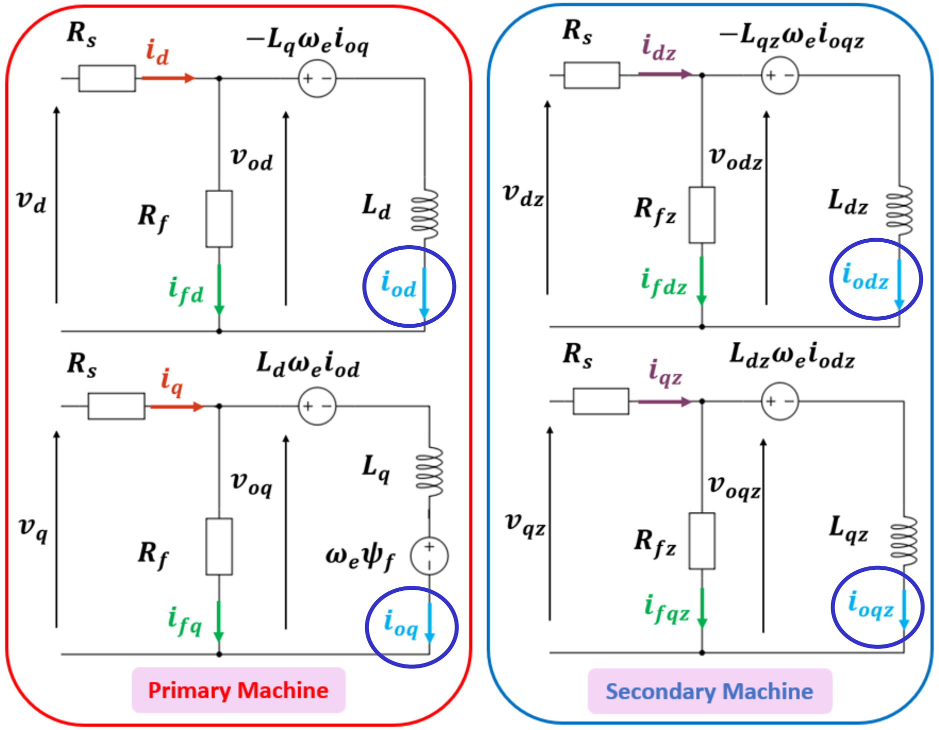


$$\frac{\hat{I}_1}{\hat{I}_2} = \frac{\Gamma_1}{\Gamma_2} = \frac{k_{\text{dist}}}{1 - k_{\text{dist}}}$$

$\hat{I}$: phase current amplitude
Γ: torque generated by one star
$0 < k_{dist} < 1$: percentage of torque from first star

$$\begin{bmatrix} i_d \\ i_q \\ i_{dz} \\ i_{qz} \end{bmatrix} = \begin{bmatrix} \hat{I}_1 + \hat{I}_2 & 0 \\ 0 & \hat{I}_1 + \hat{I}_2 \\ \hat{I}_1 - \hat{I}_2 & 0 \\ 0 & \hat{I}_1 - \hat{I}_2 \end{bmatrix} \begin{bmatrix} \cos p\theta_0 \\ -\sin p\theta_0 \end{bmatrix}$$

θ_0 is the initial angle of the rotor ($\theta_e = \omega_e t + p\theta_0$



Optimal variables (OVs):

$$x_{opt} = \begin{bmatrix} i_{o_d} & i_{o_q} & i_{o_{d_z}} & i_{o_{q_z}} \end{bmatrix}$$

Objective function (OF):

$$P_{tot}(x_{opt}) = P_{Cu}(x_{opt}) + P_{Fe}(x_{opt})$$

Torque Distribution

Constant Torque

Constraints:

$$i_{o_{q_z}} + \frac{\omega_e L_z i_{o_{d_z}}}{R_{fz}} = k\left(i_{o_q} + \frac{\omega_e L i_{o_d} + \omega_e \psi_f}{R_f}\right)$$

$$i_{o_q} = \frac{\Gamma^*_{em}}{p\psi_f}$$

« 4. Simulation Results with MATLAB/Simulink »

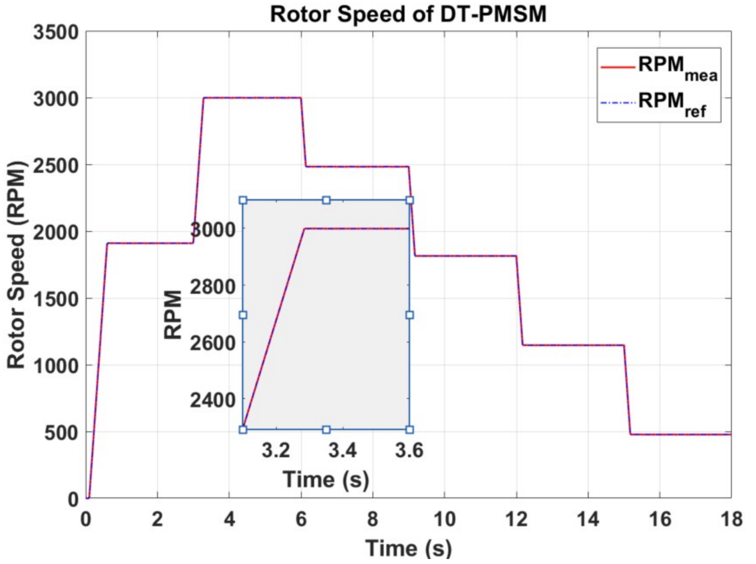
TABLE I: DT-PMSM System Parameters

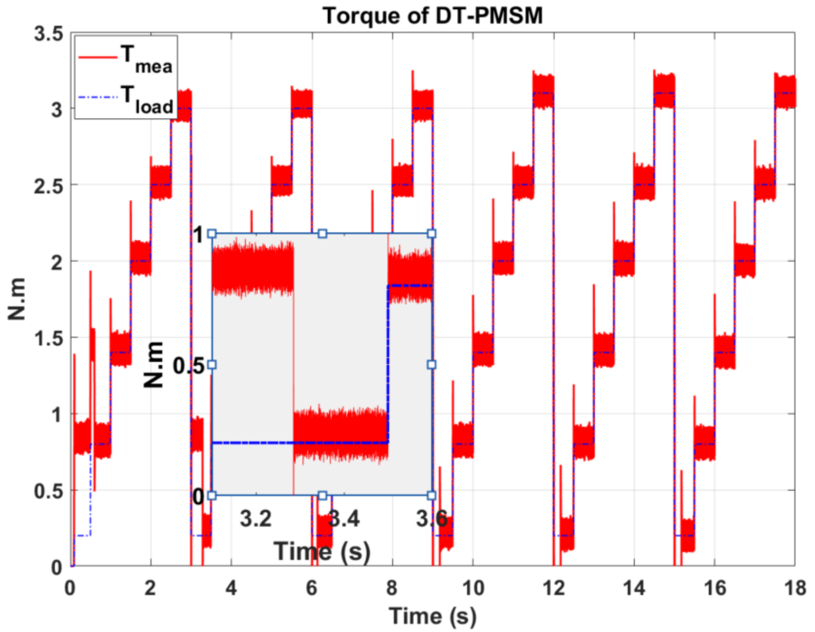
Symbol	Parameters	Value and unit
Γ_n	Nominal torque	3.2 N·m
N_n	Nominal speed	4500 rpm
p	Pole pairs	4
R_s	Stator resistance	0.435 Ω
R_f	dq-axix iron loss equivalent resistance	600 Ω
R_{f_z}	$d_z q_z$-axix iron loss equivalent resistance	600 Ω
L	Inductance in dq axis	0.0090 H
L_z	Leakage inductance in $d_z q_z$ axis	0.0015 H
γ	Stator spatial displacement	$\pi/6$ rad
ψ_f	Flux linkage	0.086 Wb·T

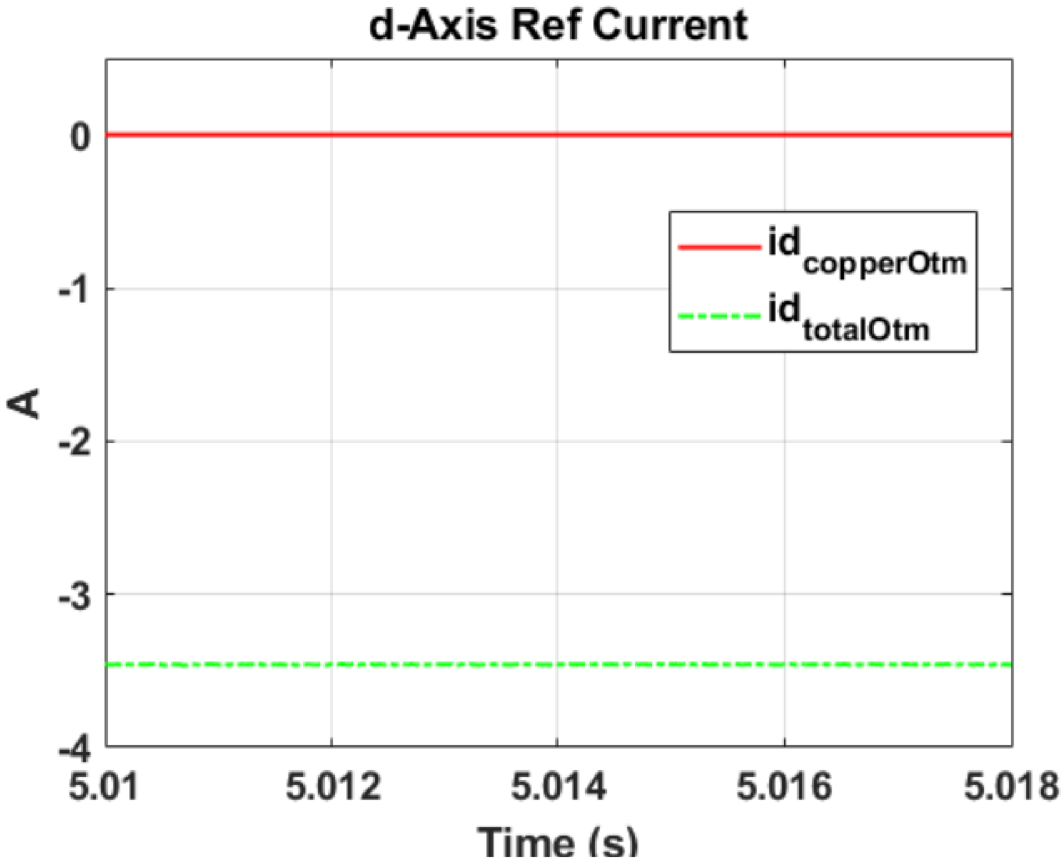
Simulation Scenario:

- Investigate in different torque-speed steps
- **Compare** loss and high-efficiency region between **Maximum Torque Distribution per Loss** with **Maximum Torque Distribution per Ampere.**
- Neglect Flux-Weakening effect (constant rotor flux)
- Choose specific value for Iron Loss resistance to test the Control Method

4.2 Simulation Results under Torque Distribution condition



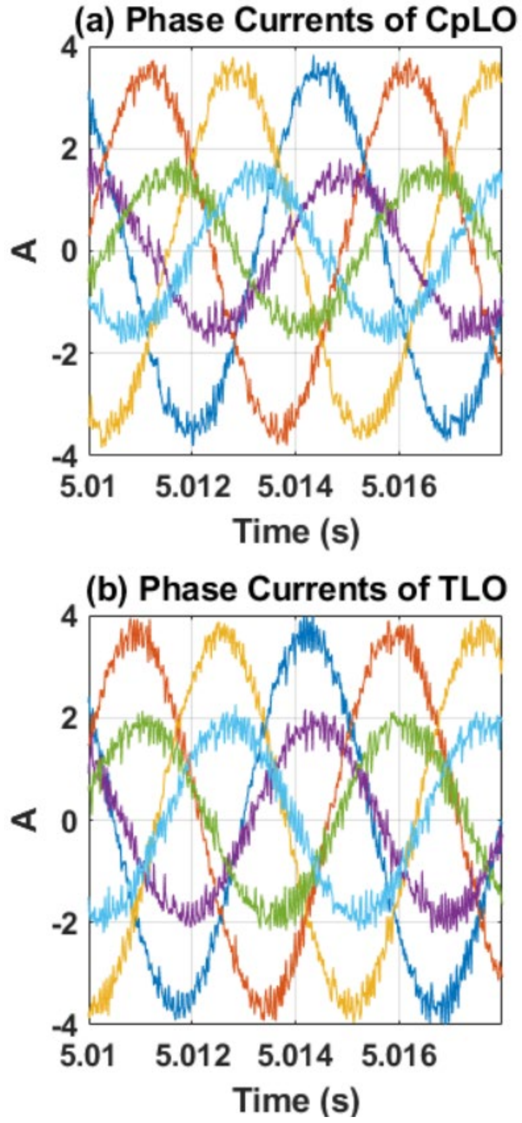


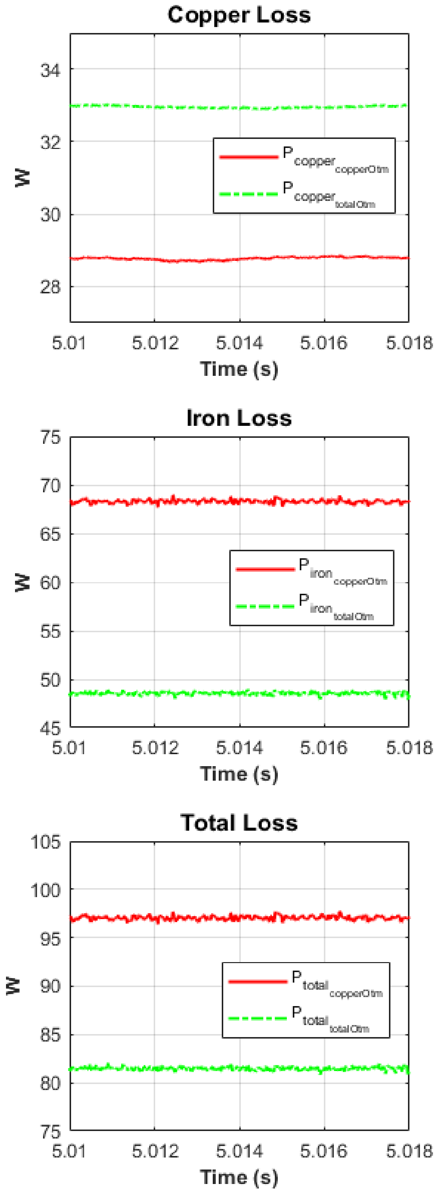


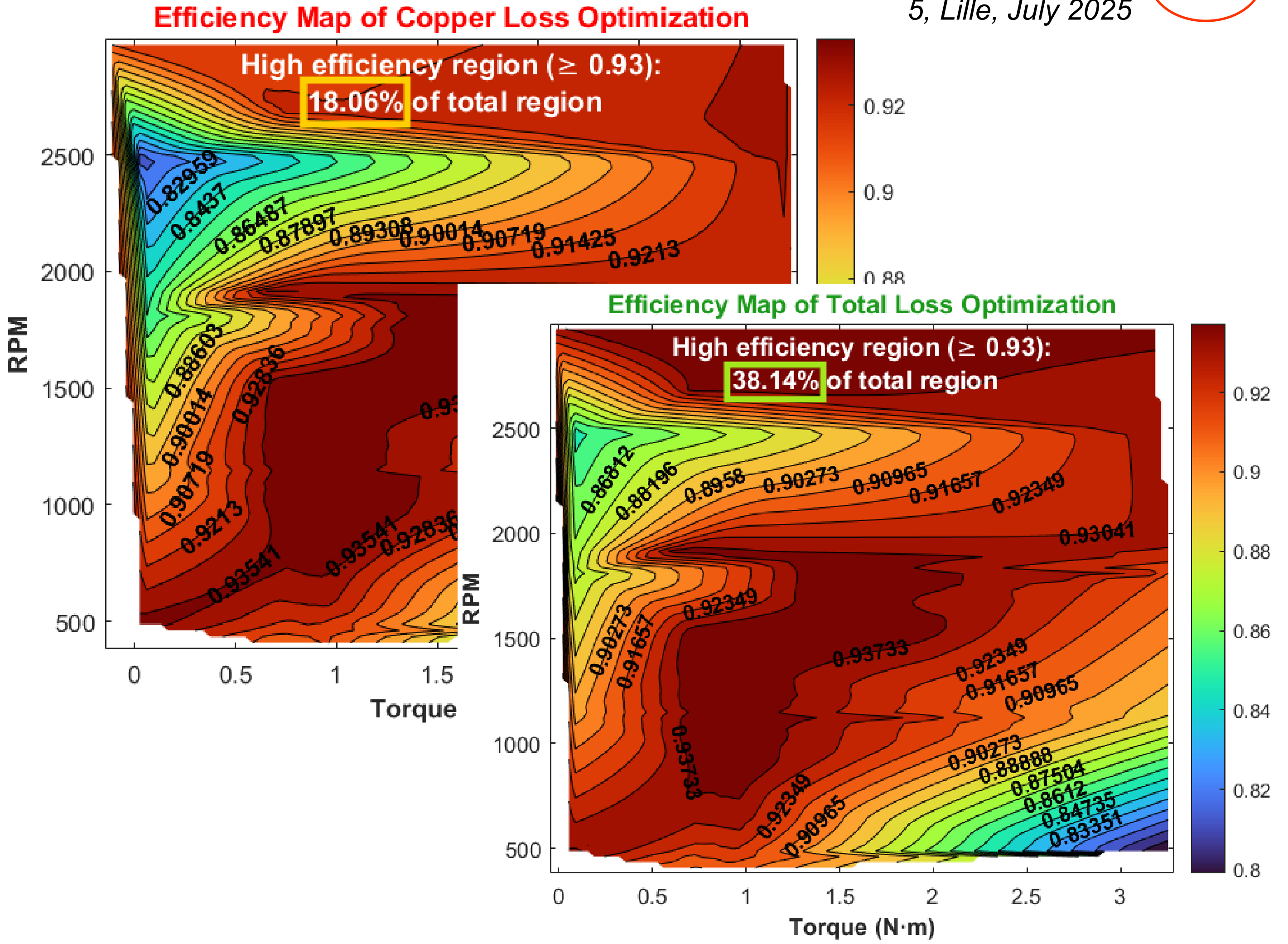
Red: Maximum Torque Distribution per Ampère

Green: Maximum Torque Distribution per Loss

4.2 Simulation Results under Torque Distribution condition 0.7-0.3

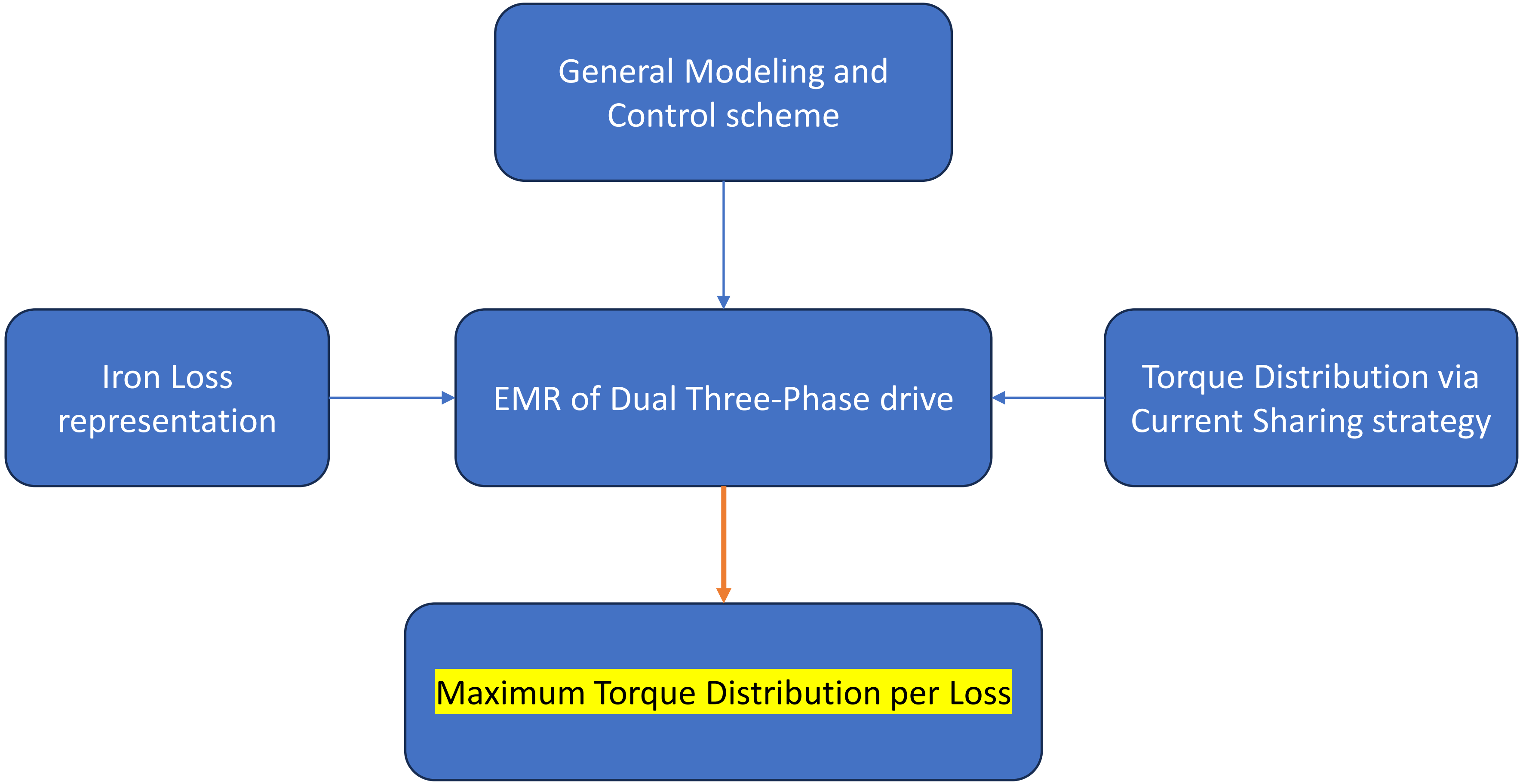






Red: Maximum Torque Distribution per Ampère (MTPA)
Green: Maximum Torque Distribution per Loss (MTPL)

« 5. Conclusion»



Future Works:

- Calculate Iron Loss resistance with FEM, Neural Network
- Consider the transient time in optimal control

Thanks for your attention !

- Authors -

Le Tam PHAM, ENSAM, L2EP,
Master 2 Electrical Engineering for Sustainable Development
le_tam.pham@ensam.eu

Prof. Ngac Ky NGUYEN, ENSAM, L2EP,
IEEE Member,
PhD in Electrical Engineering at Université de Haute Alsace
Research topics: Electrical Machines and Drives, Multiphase Machine Control, …
ngacky.nguyen@ensam.eu

[Bouscayrol 2000] A. Bouscayrol, & al. "Multimachine Multiconverter System: application for electromechanical drives", *European Physics Journal - Applied Physics,* vol. 10, no. 2, May 2000, pp. 131-147 (common paper GREEN Nancy, L2EP Lille and LEEI Toulouse, according to the SMM project of the GDR-SDSE).

[Bouscayrol 2012] A. Bouscayrol, J. P. Hautier, B. Lemaire-Semail, "Graphic Formalisms for the Control of Multi-Physical Energetic Systems", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 3, ISTE Willey editions, October 2012, ISBN: 9781848213883

[Bouscayrol 2023] A. Bouscayrol, B. Lemaire-Semail, "Energetic Macroscopic Representation and Inversion-Based Control ", Encyclopedia of electrical and electronic power engineering, Vol. 3, pp 365-375, Elesevier, DOI : 10.1016/B978-0-12-821204-2.00117-3, ISBN : 978-0-12-823211-8, 2023

[Vu 2019] D. T. Vu, N. K. Nguyen, E. Semail, and W. Lhomme, 'Electric Vehicles Driven by 5-Phase Open-End Winding Machines Fed by Battery and Supercapacitors', in *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Oct. 2019, pp. 1–6. doi: 10.1109/VPPC46532.2019.8952562.