Free-Most Project

BANDO PUBBLICO PER LA SELEZIONE DI PROPOSTE PROGETTUALI, FINALIZZATE ALLA CONCESSIONE DI FINANZIAMENTI PER ATTIVITÀ COERENTI CON GLI OBIETTIVI DEL CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE, A VALERE SULLE RISORSE DEL PIANO NAZIONALE RIPRESA E RESILIENZA (PNRR) MISSIONE 4, "ISTRUZIONE E RICERCA" - COMPONENTE 2, "DALLA RICERCA ALL'IMPRESA" - LINEA DI INVESTIMENTO 1.4 "CENTRI NAZIONALI", FINANZIATO DALL'UNIONE EUROPEA – NEXTGENERATIONEU" PROGETTO CNMS – Centro Nazionale Mobilità Sostenibile – Codice Identificativo CN00000023, SPOKE 12 – SUSTAINABLE PROPULSION – CUP B43C22000440001

Presenter: Davide Liuzza (University of Sannio)

June 19th, 2025

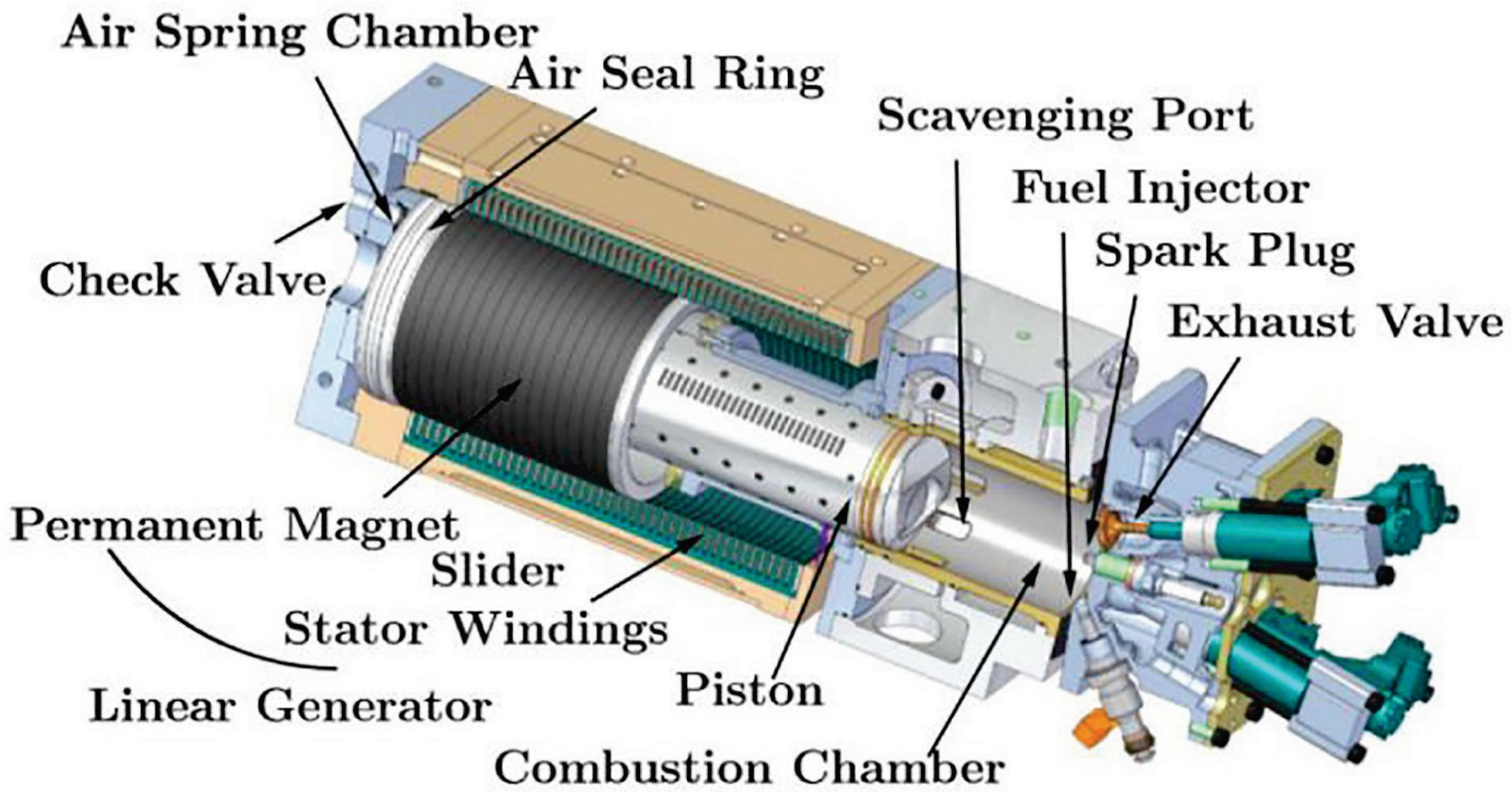
Project overview

- Name: **Free-Most**
- Duration: **10 months** (started on August 2024)
- Budget: **270.000 €**
- Partners:
  - **University of Sannio**
  - **CNR – STEMS**
  - **Vanvitelli University**

Project aim in brief

- Modeling study of free piston linear generator (FPLG) system with a specific focus on the electromagnetic part jointly with power converter and a battery
- Control system study and design for a FPLG coupled with battery
- Digital twin development for the system FPLG + power converter + battery
- Magnetic design of a FPLG
- Desing and setup of an experimental test rig for a FPLG system

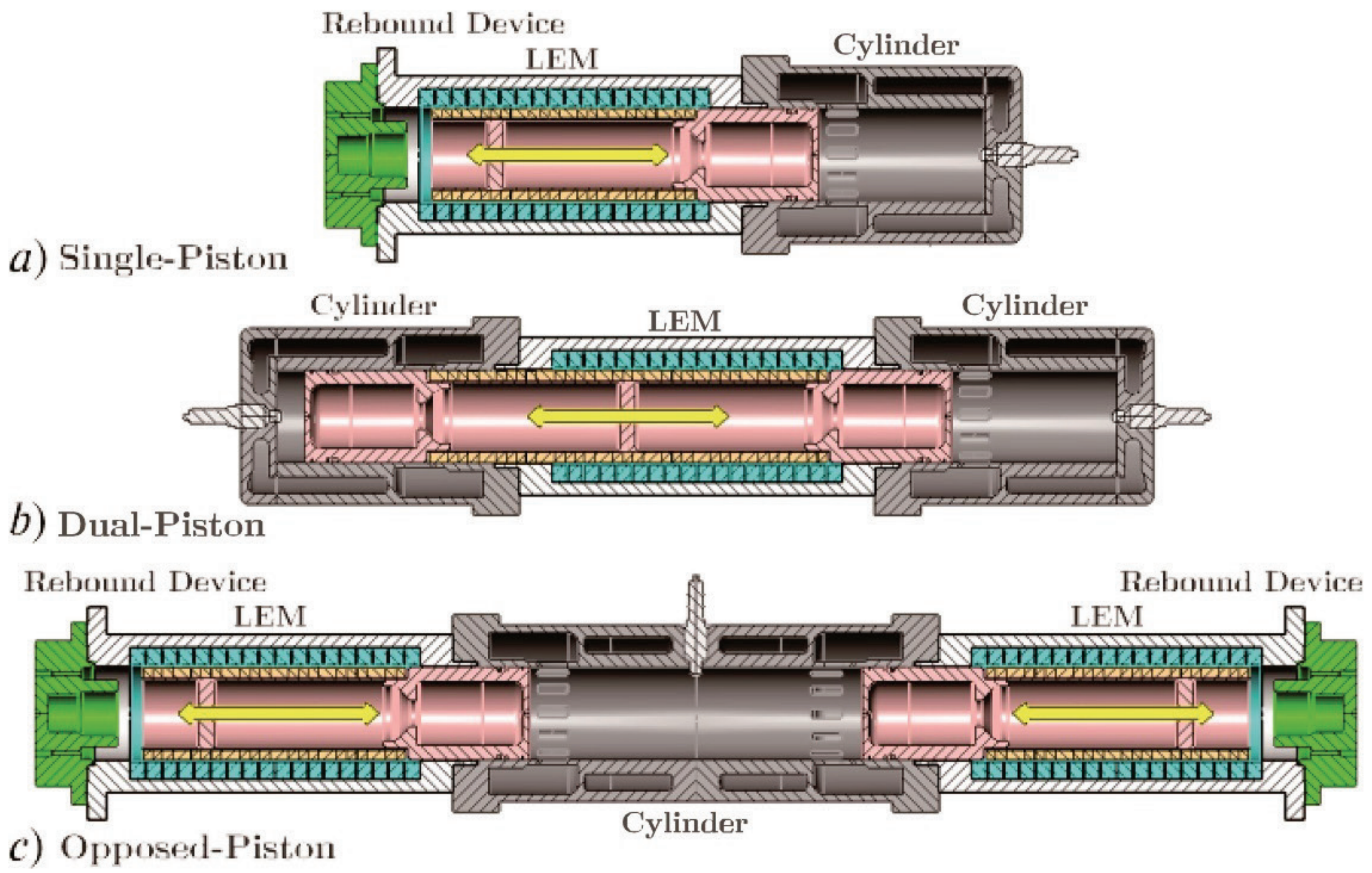
What is a FPLG?



A Toyota gas FPLG

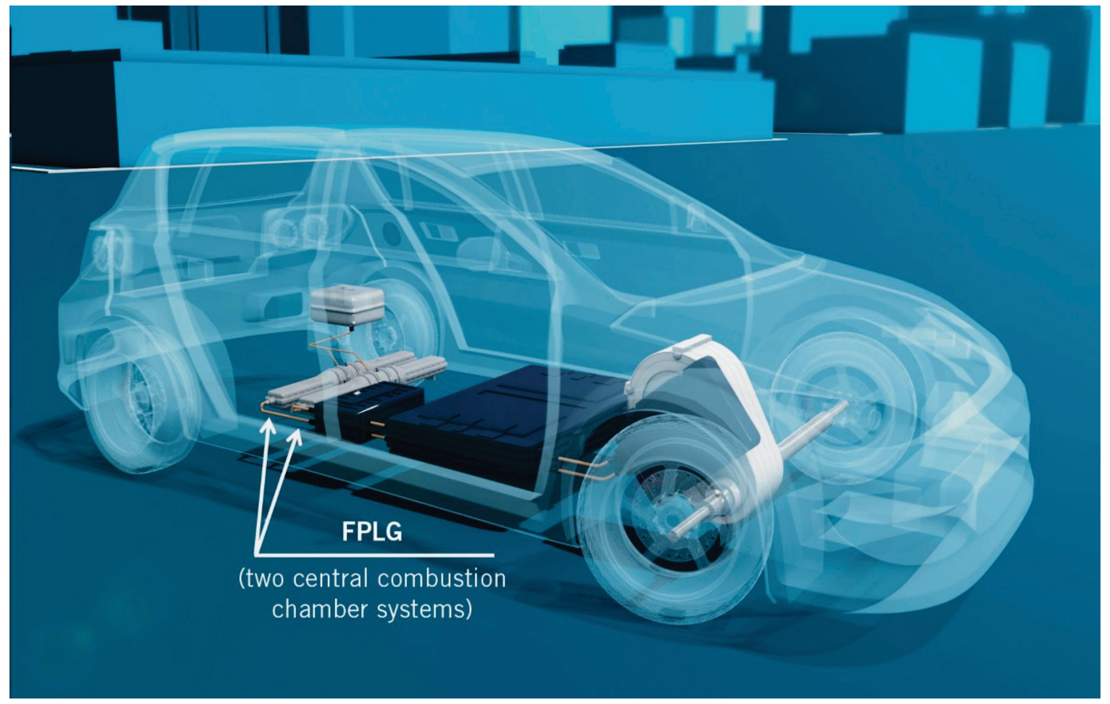
- Main components:
  - Combustion chamber(s)
  - Linear electric motor/generator (permanent magnets on the mover)
  - Rebound chamber

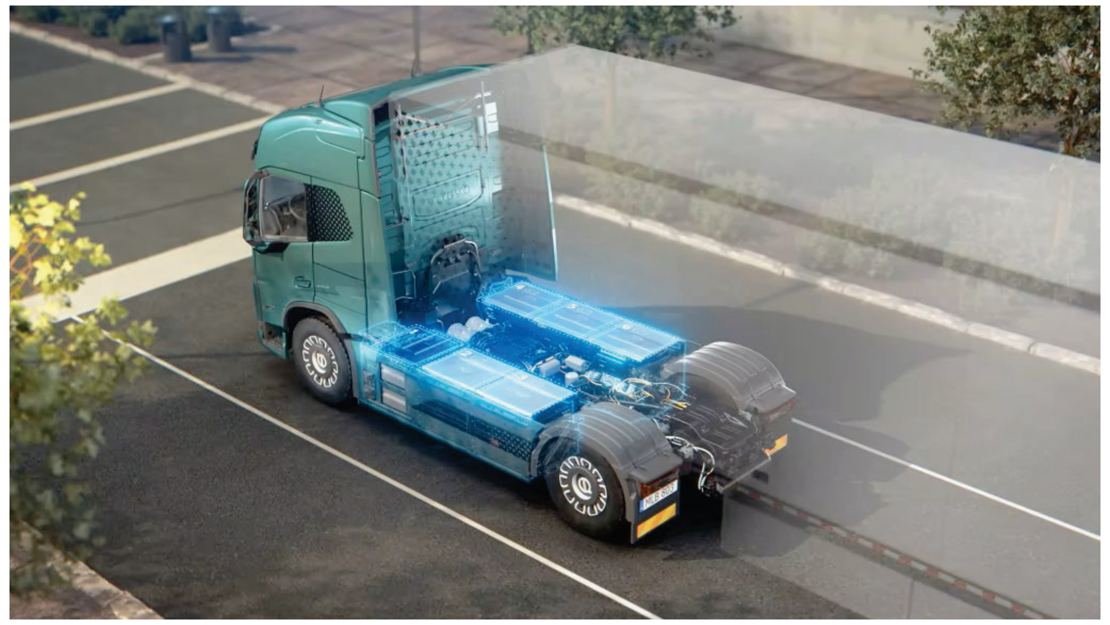
- Main configurations



Motivation

- The EU has clearly set its sights on battery electric mobility
- Large sectors of transportation (especially heavy vehicles, work machinery and shipping) are ill-suited for battery storage-based traction
- Battery-powered cars are not experiencing the expected market growth:
  - Insufficient recharging infrastructure
  - higher costs compared to traditional traction (both vehicles and recharges)
- Battery based solutions do not guarantee, at the moment, EU independence from battery producers, especially China





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- Need for technical solutions for large transportation sectors
- Need for economically feasible transitions solution (CO_2 reduction despite immature infrastructure)
- Need for strategic alternatives

Advantages of FPLG solutions

Automotive

- FPLGs represent a potential alternative for range-extender automotive solutions
  - Less vibrations and noise due to the absence of crankshaft
  - Higher potential efficiency due to reduced friction forces
  - Adaptable combustion chamber
  - Multi-fuel

- High potential in the Italian automotive market (a green transition acceptable by consumers) allowing for high production values:
  - Italian engineering industry invoices about 400 billions € (8% of GDP)
  - Italian engineering industry accounts for more than half of Italy's exports

Other sectors

- Due to its compact size, FPLG can be also envisioned for:
  - Uninterrupted/Emergency power systems
  - Auxiliary power units for aircrafts, ships and large vehicles
  - Residential co-generation units

Challenges of FPLG

- Difficult to control the FPLG motion/generation due to non-constant velocities of the piston
- Difficult to integrate battery and converter models with the FPLG model
- Difficult to handle fluctuating currents for battery recharging
- Lack of sufficient theoretical and experimental studies for specific range extender applications

- As said, the Free-Most projects aims to address these issues

Modeling - overview

- The modeling has been conducted under some constructive assumptions:
  - Opposed piston with perfectly symmetric forces, i.e., reduced to the single piston case
  - Ideal gas assumption
  - Lumped parameters, uniform temperature and gas pressure
  - Three-phase motor
  - Only self inductance is considered for each coil

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Modeling - scheme

- z, v position, velocity
- p_c chamber pressure
- i_{rst} currents
- e_{rst} voltages
- Φ_{rst} magnetic flows
- σ_{rst} switch signals
- i_{dc} battery current
- SoC state of charge

Mechanical model

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = A_c p_c - A_r p_r + F_e(z, i_{rst}) - F_f(p_c, v) - F_f(p_r, v)$$

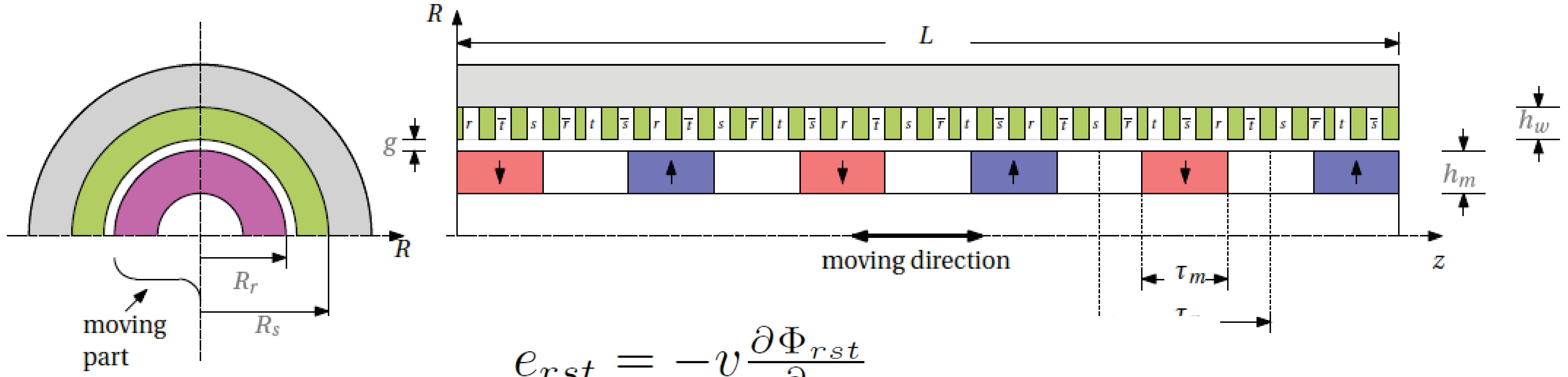
$$\frac{\mathrm{d}z}{\mathrm{d}t} = v$$

z, v, i_{rst}

p_c, z, v

i_{rst}, e_{rst}

Magnetic model



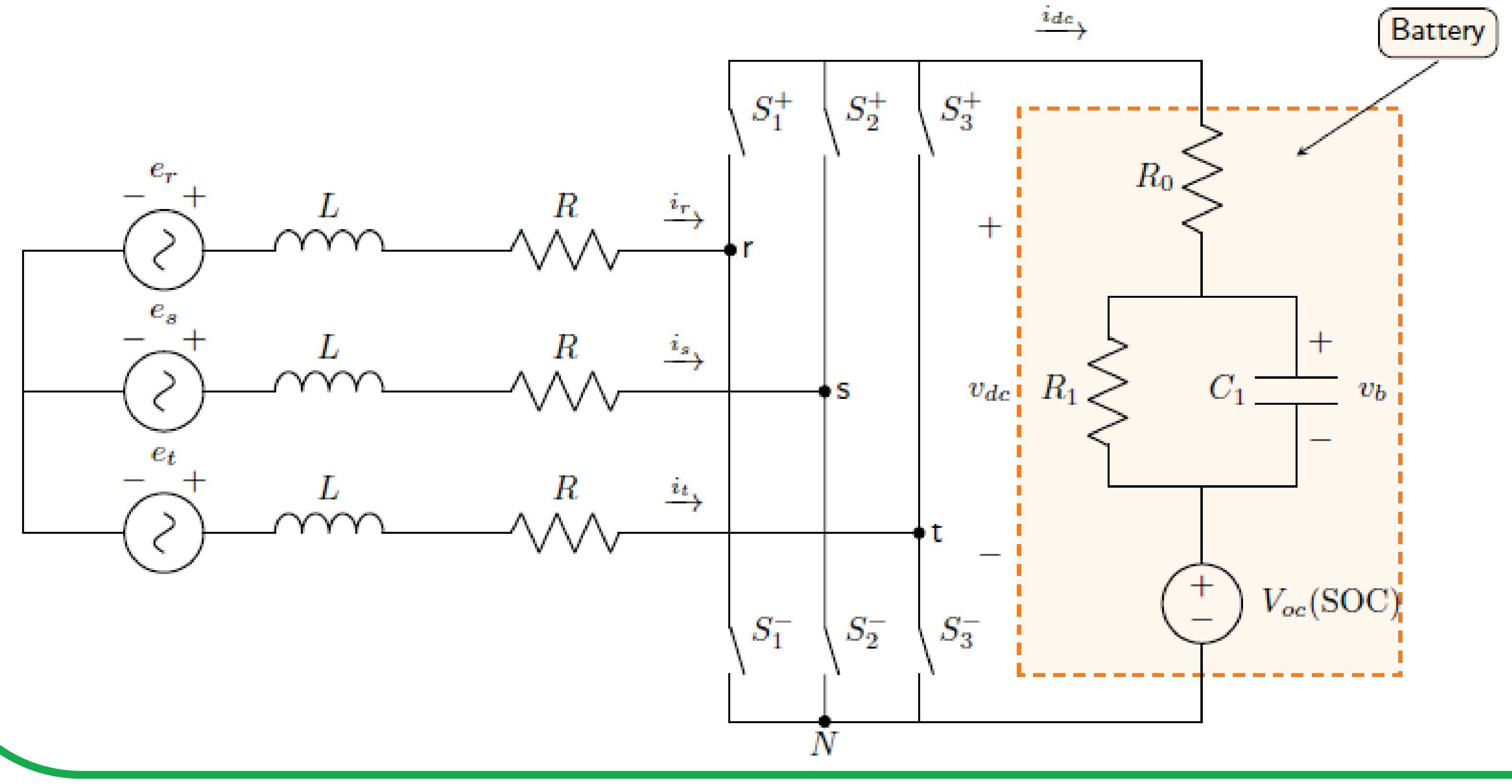
$$e_{rst} = -v\frac{\partial \Phi_{rst}}{\partial z}$$

$$F_e(z, i_{rst}) = \frac{1}{v} e_{rst}^\top i_{rst} = -\frac{\partial \Phi_{rst}^\top}{\partial z} i_{rst}$$

Thermodynamical model

$$\frac{\mathrm{d}p_c}{\mathrm{d}t} = \frac{\gamma - 1}{A_c z + V_0}\left(\dot{Q}_c - \dot{Q}_{ht}(p_c, z)\right) - \frac{p_c\gamma}{m_{\mathrm{air}}}\frac{\mathrm{d}m_{\mathrm{air}}}{\mathrm{d}t} - \frac{A_c p_c \gamma}{A_c z + V_0} v$$

Electric model



$$L\frac{\mathrm{d}i_{\alpha\beta}}{\mathrm{d}t} = -Ri_{\alpha\beta} + e_{\alpha\beta} - \sigma_{\alpha\beta}v_{dc}$$

$$C_1\frac{\mathrm{d}v_b}{\mathrm{d}t} = -\frac{1}{R_1}v_b + i_{dc}$$

$$\frac{\mathrm{d}SoC}{\mathrm{d}t} = \frac{1}{Q}i_{dc}$$

$$\sigma_{\alpha\beta}^\top i_{\alpha\beta} = \frac{2}{3}\sigma_{rst}^\top i_{rst} = \frac{2}{3}i_{dc}$$

- S. Baccari, C. Beatrice, C. Capasso, …., O. Veneri, “Integration of free piston linear generator and battery pack in hybrid vehicles”, ESARS-ITEC 2024

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Control – assumptions

- For the three phase model a control has been derived

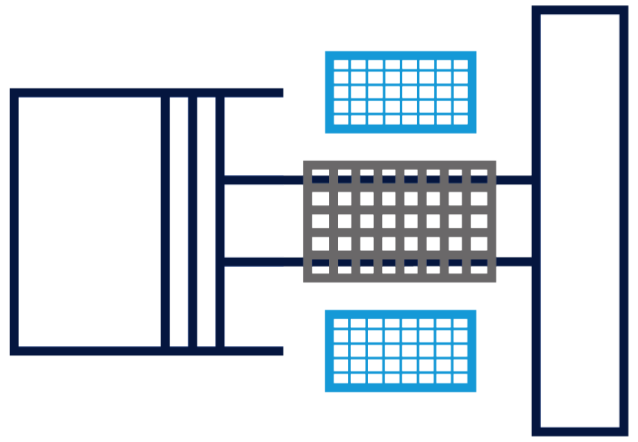
- This control is meant for the project envisioned test rig:
  - The piston is moved according to a mover which emulates the combustion expansion and rebound (or any periodic movement)
  - The current generation is controlled so as to recharge a battery

- Fast switching (averaging) assumption:
  - Signals of the switches are continuous in the interval [0,1]

❖ E. Mostacciuolo, S. Baccari, C. Beatrice, L. Rubino, …., F. Vasca, "Power extraction for free piston linear generator", ICCEP 2025

Control – piston movement

- We consider a harmonic movement of the piston to design the controller



v

$$v = V\cos\theta_m$$

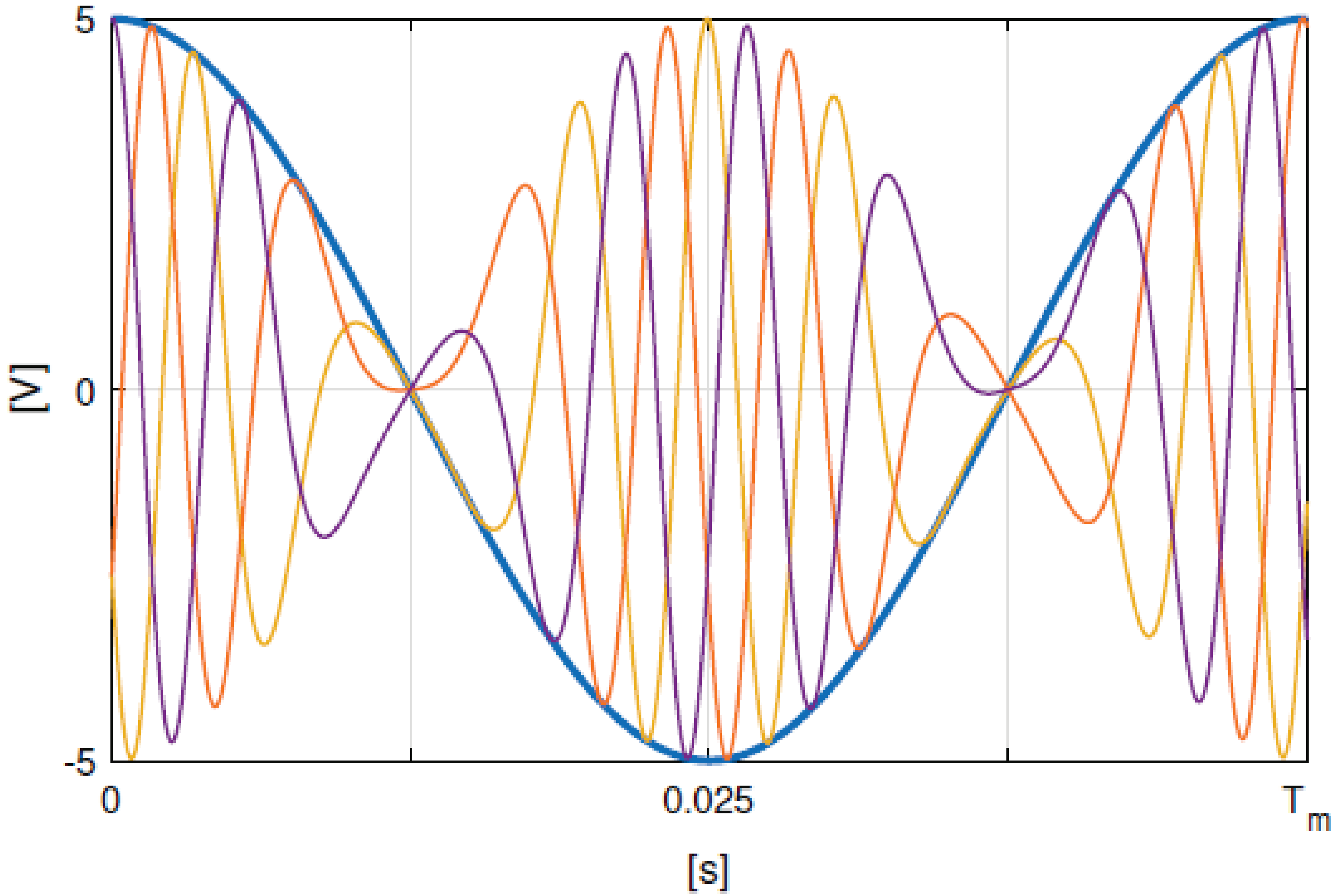
$$\theta_m = \omega_m t,\ \omega_m = 2\pi/T_m$$

complete trip (forward-backward) period

$$e_{rst} = \varphi v \begin{pmatrix} \cos\theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{pmatrix}$$

electrical phase

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{\hat{\mu}}{V}\omega_m|v| = \mu\omega_m|v|$$



Time evolution of v and normalized voltages e_{rst}/φ

Control – Clarke transformation and notch filter

- Three phase

$$L\frac{\mathrm{d}x_r}{\mathrm{d}t} = -Rx_r + e_r - e_s + L\frac{\mathrm{d}x_s}{\mathrm{d}t} + Rx_s - (q_r - q_s)e_b$$

$$L\frac{\mathrm{d}x_s}{\mathrm{d}t} = -Rx_s + e_s - e_t + L\frac{\mathrm{d}x_t}{\mathrm{d}t} + Rx_t - (q_s - q_t)e_b$$

$$L\frac{\mathrm{d}x_t}{\mathrm{d}t} = -Rx_t + e_t - e_r + L\frac{\mathrm{d}x_r}{\mathrm{d}t} + Rx_r - (q_t - q_r)e_b$$

- Switches

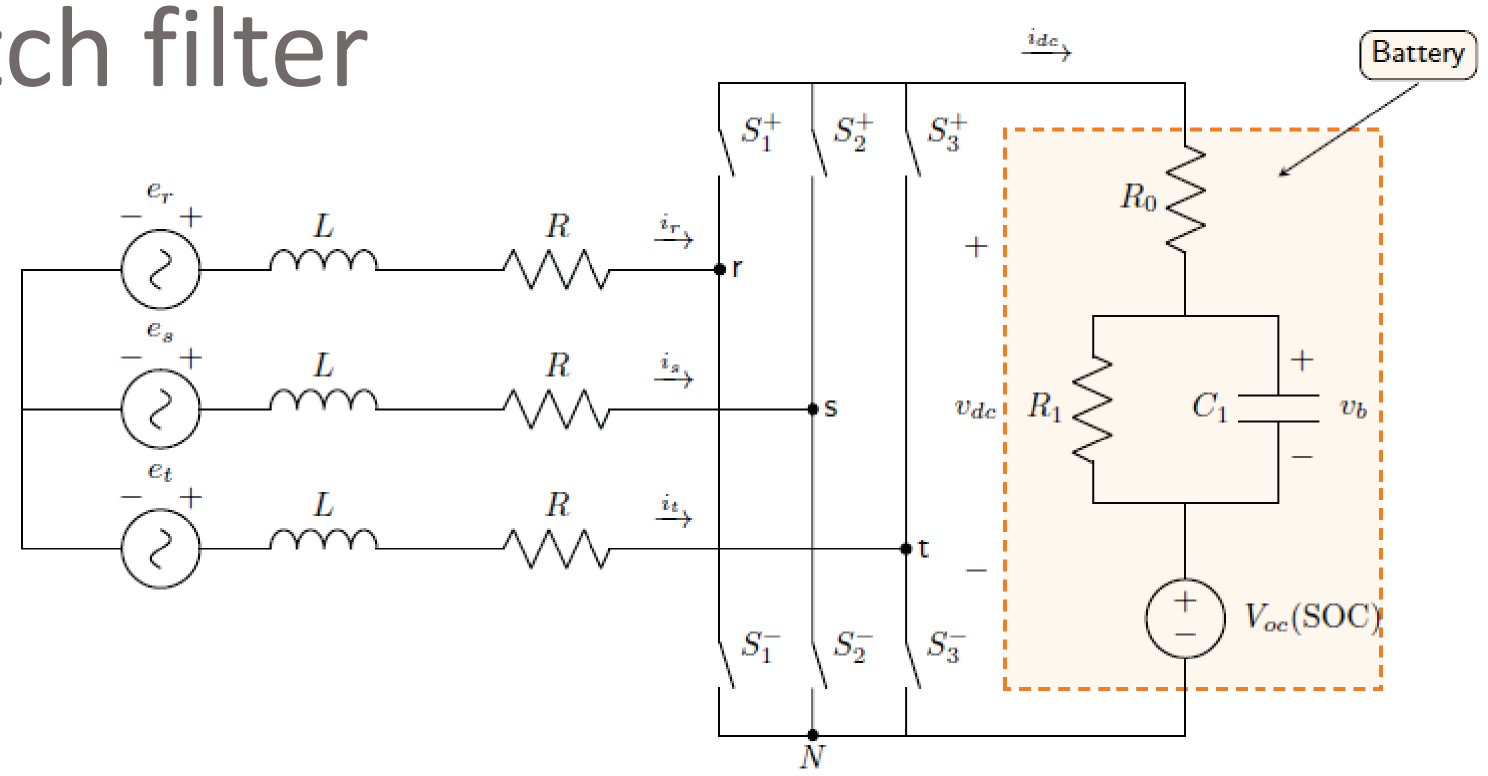
$$q_j = \begin{cases} 1 & \text{if } S_j^+ \text{ is on and } S_j^- \text{ is off} \\ 0 & \text{otherwise} \end{cases}$$

$$\Big\Downarrow \text{ Clarke transformation}$$

$$L\frac{\mathrm{d}i_{\alpha\beta}}{\mathrm{d}t} = -Ri_{\alpha\beta} + e_{\alpha\beta} - \sigma_{\alpha\beta}e_b$$

$$e_{\alpha\beta} = \varphi v \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$

Control – Clarke transformation and notch filter



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Control – Clarke transformation and notch filter

- Three phase

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Clarke transformation

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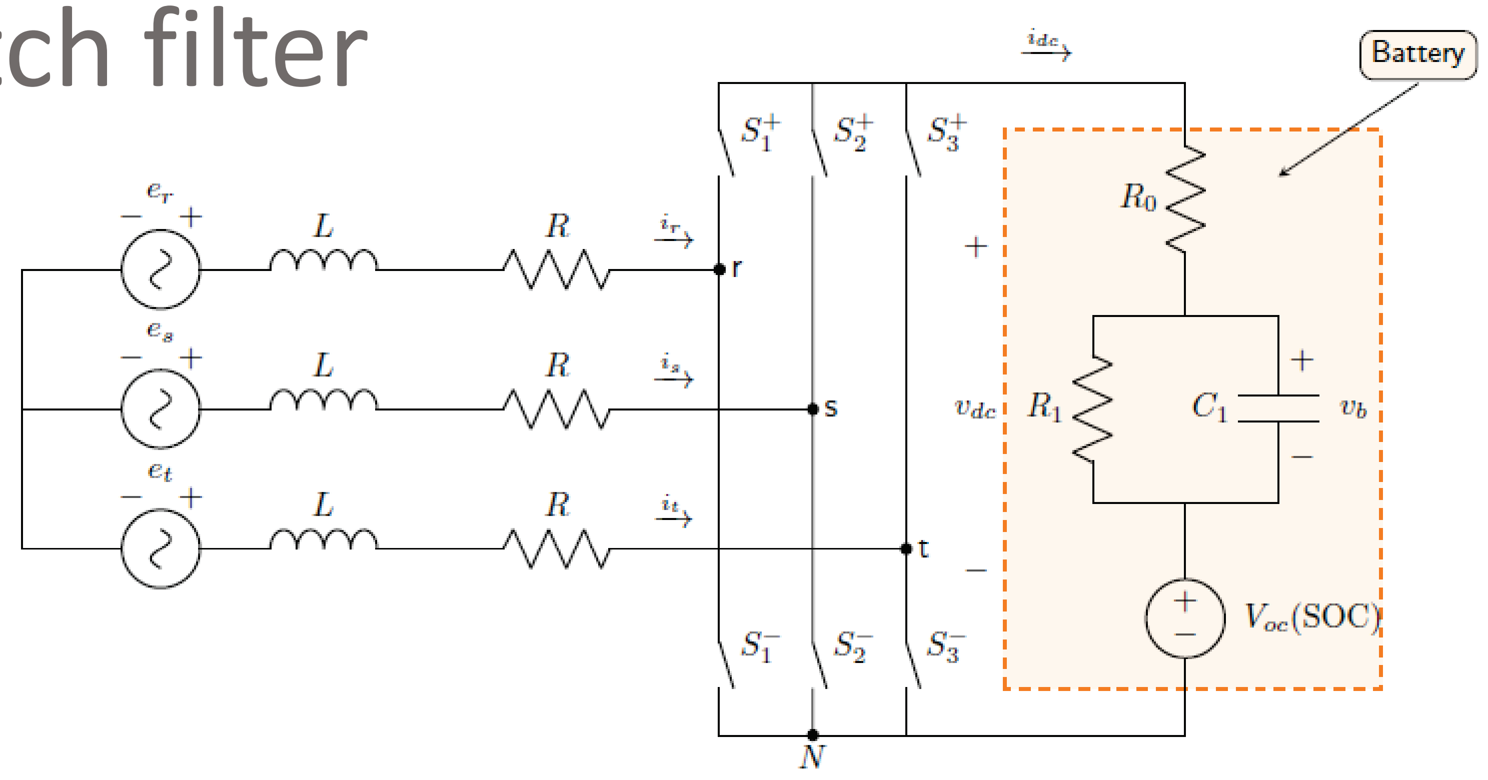
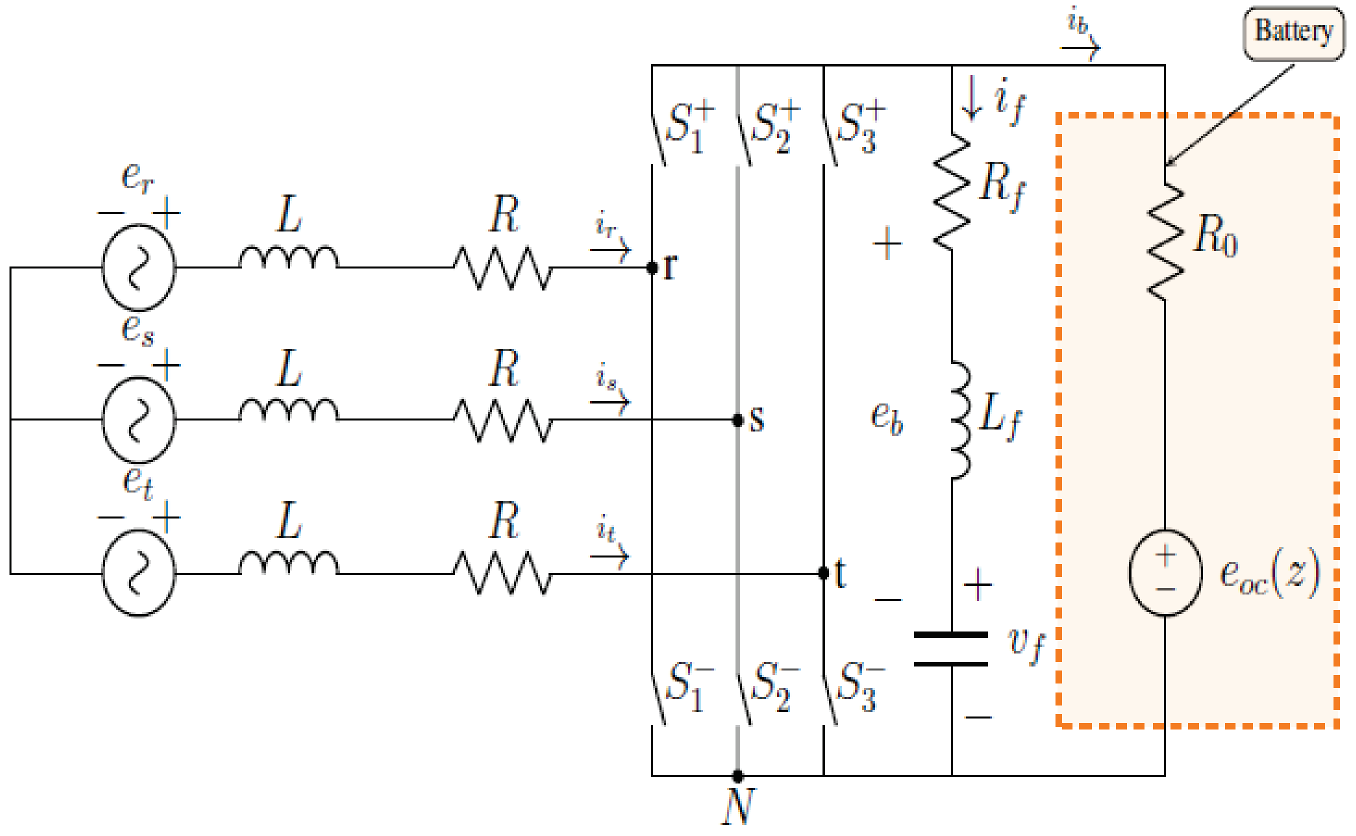


A notch filter is added



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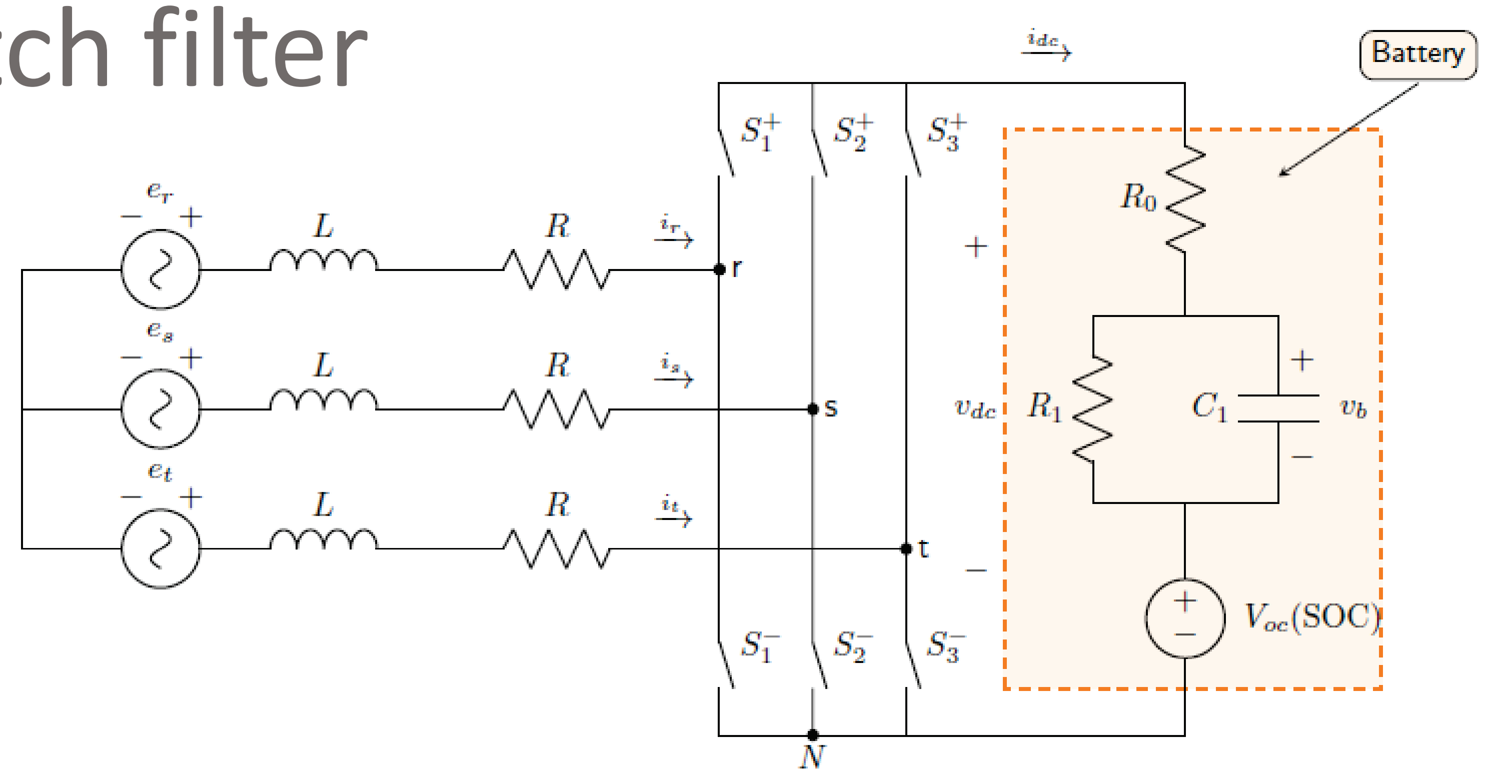
Control – Clarke transformation and notch filter



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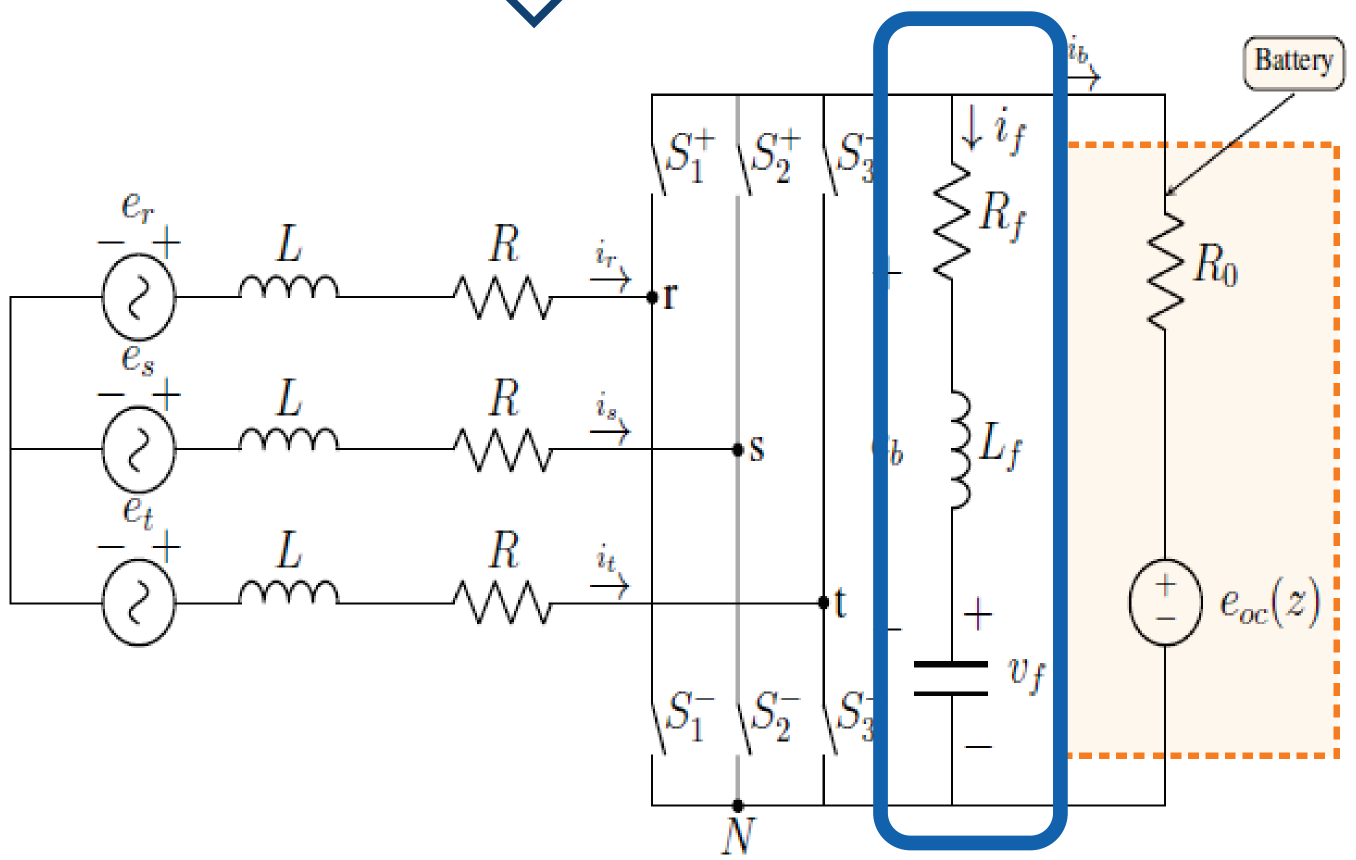


Control – Filter and battery

- Current from the FPLG

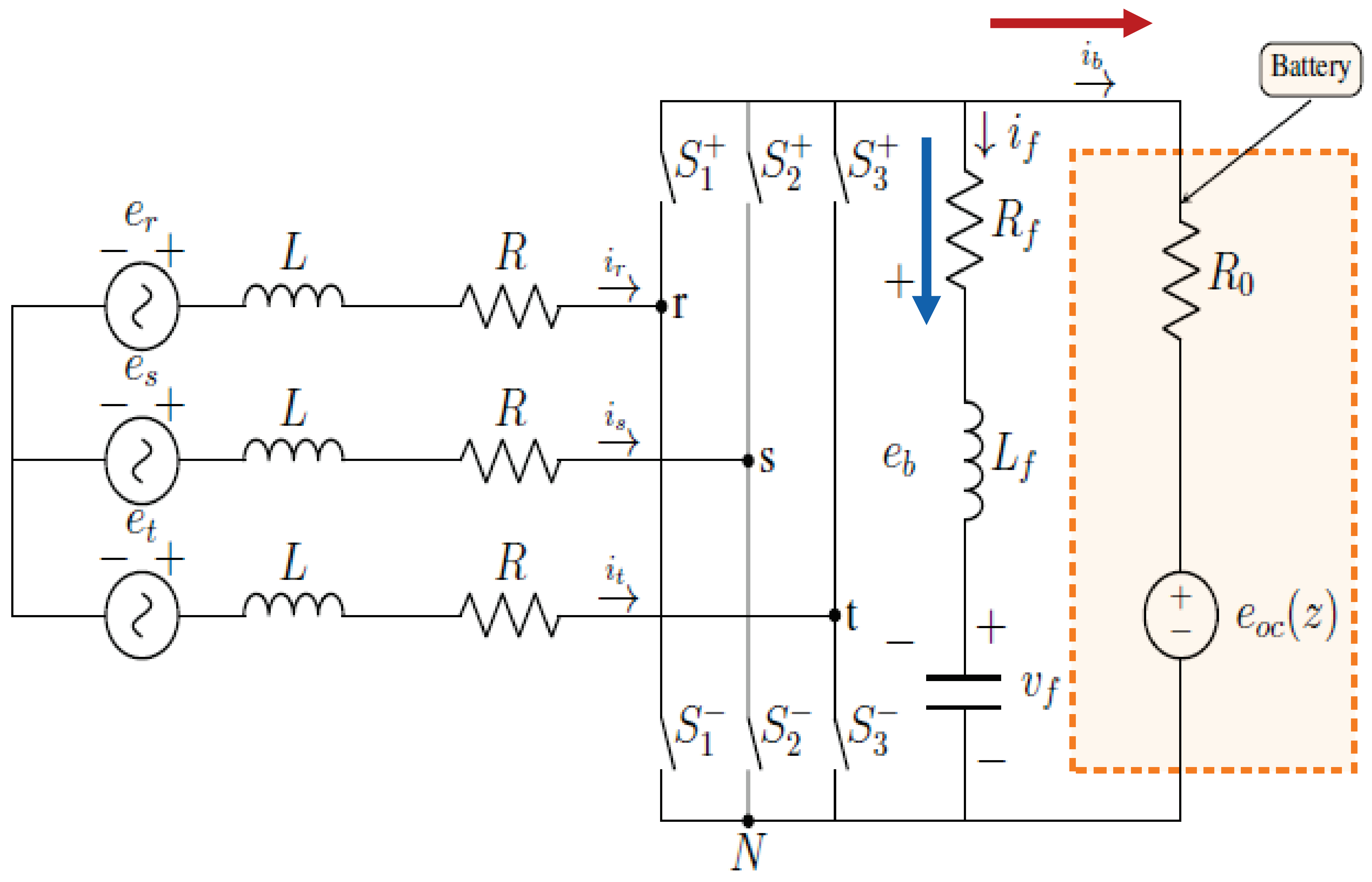
$$\sigma_{\alpha\beta}^{\top} i_{\alpha\beta} = \frac{2}{3} y$$
$$y = i_b + i_f$$

- Filter

$$L_f \frac{\mathrm{d}i_f}{\mathrm{d}t} = -R_f i_f - v_f + e_b$$
$$C_f \frac{\mathrm{d}v_f}{\mathrm{d}t} = i_f$$

- Battery

$$Q \frac{\mathrm{d}z}{\mathrm{d}t} = i_b$$



Control – direct/quadrature transformation

$$i_{dq} = \Gamma(\theta) i_{\alpha\beta}$$

$$e_{dq} = \Gamma(\theta) e_{\alpha\beta}$$

$$\Gamma(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\Big\Downarrow$$

Direct/quadrature transformation

$$L\frac{\mathrm{d}i_d}{\mathrm{d}t} = -Ri_d + \mu|v|\omega_m L i_q + \varphi v - \sigma_d e_b$$
$$L\frac{\mathrm{d}i_q}{\mathrm{d}t} = -\mu|v|\omega_m L i_d - Ri_q - \sigma_q e_b$$
$$y = \frac{3}{2}(\sigma_d i_d + \sigma_q i_q)$$

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$$y = \frac{3}{2}(\sigma_d i_d + \sigma_q i_q)$$

σ_q control is designed to have $i_q = 0$ at steady state

- Quadrature control

$$\sigma_q = -\frac{\mu|v|\omega_m L i_d}{e_b}$$

$$L\frac{\mathrm{d}i_d}{\mathrm{d}t} = -Ri_d + \varphi V\cos\theta_m - \sigma_d e_b$$

$$y = \frac{3}{2}\sigma_d i_d$$

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$$y = \frac{3}{2}\sigma_d i_d$$

Decomposed as steady state + sinusoidal solution

Control – decomposition steady state + sinusoidal

- Sinusoidal solution form

$$i_d = i_{da} \cos\theta_m + i_{db} \sin\theta_m$$

$$\sigma_d = \sigma_{da} \cos\theta_m + \sigma_{db} \sin\theta_m$$

$$\Downarrow$$

$$\frac{2}{3} y = \frac{\sigma_{da} i_{da} + \sigma_{db} i_{db}}{2} + \frac{\sigma_{da} i_{da} - \sigma_{db} i_{db}}{2} \cos 2\theta_m + \frac{\sigma_{da} i_{db} + \sigma_{db} i_{da}}{2} \sin 2\theta_m$$

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$$i_d = i_{da}\cos\theta_m + i_{db}\sin\theta_m$$

$$\sigma_d = \sigma_{da}\cos\theta_m + \sigma_{db}\sin\theta_m$$

$$\frac{2}{3}y = \frac{\sigma_{da}i_{da}+\sigma_{db}i_{db}}{2} + \cancel{\frac{\sigma_{da}i_{da}-\sigma_{db}i_{db}}{2}\cos 2\theta_m + \frac{\sigma_{da}i_{db}+\sigma_{db}i_{da}}{2}\sin 2\theta_m}$$

Removed by the filter

$$i_b = \frac{3}{4}(\sigma_{da}i_{da}+\sigma_{db}i_{db})$$

Control – decomposition steady state + sinusoidal

- Sinusoidal solution form

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$$\sigma_d = \sigma_{da}\cos\theta_m + \sigma_{db}\sin\theta_m$$

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Removed by the filter

$$i_b = \frac{3}{4}(\sigma_{da}i_{da} + \sigma_{db}i_{db})$$

- Feedback and feedforward control decomposition

$$\sigma_{da} = \sigma_{da}^{\mathrm{ff}} + \sigma_{da}^{\mathrm{fb}}$$
$$\sigma_{db} = \sigma_{db}^{\mathrm{ff}} + \sigma_{db}^{\mathrm{fb}}$$

Control – decomposition steady state + sinusoidal

- Sinusoidal solution form

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$$i_b = \frac{3}{4}(\sigma_{da}i_{da} + \sigma_{db}i_{db})$$

- Feedback and feedforward control decomposition

$$\sigma_{da} = \sigma_{da}^{\text{ff}} + \sigma_{da}^{\text{fb}}$$
$$\sigma_{db} = \sigma_{db}^{\text{ff}} + \sigma_{db}^{\text{fb}}$$

$$\sigma_{da}^{\text{ff}} = \frac{-Ri_{da}^{\text{ref}} + \varphi V}{e_b}$$

$$\sigma_{db}^{\text{ff}} = -\frac{\omega_m L i_{da}^{\text{ref}}}{e_b}$$

FF is designed to keep the steady state solution

$$L\frac{\mathrm{d}\hat{i}_{da}}{\mathrm{d}t} = -R\hat{i}_{da} + \omega_m L\hat{i}_{db} - \sigma_{da}^{\text{fb}}e_b$$
$$L\frac{\mathrm{d}\hat{i}_{db}}{\mathrm{d}t} = -\omega_m L\hat{i}_{da} - R\hat{i}_{db} - \sigma_{db}^{\text{fb}}e_b$$

$$u_{da} = \omega_m L\hat{i}_{db} - \sigma_{da}^{\text{fb}}e_b$$
$$u_{db} = -\omega_m L\hat{i}_{da} - \sigma_{db}^{\text{fb}}e_b$$

FB is designed with feedback linearization + PD

Control – numerical analysis

- A digital twin of the FLPG + Battery + Control has been developed in Matlab/Simulink

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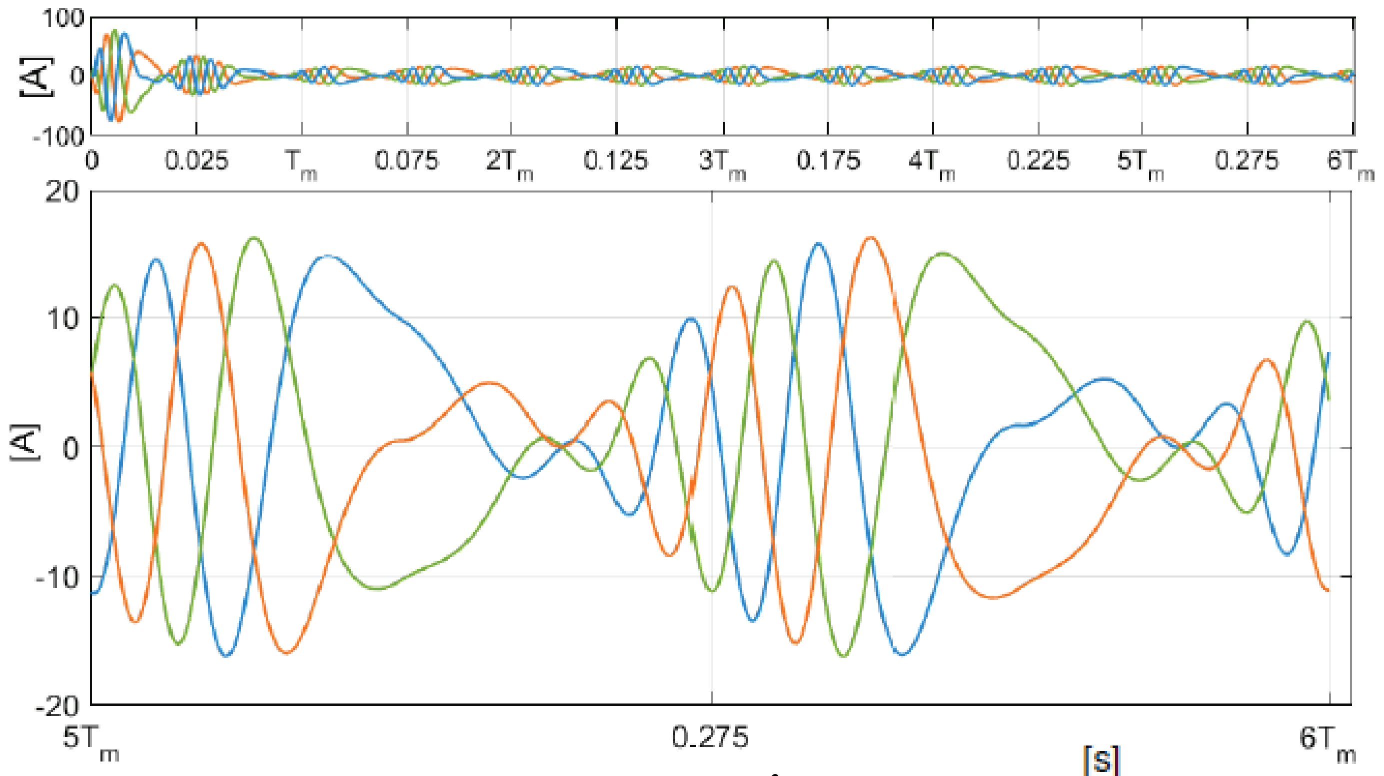
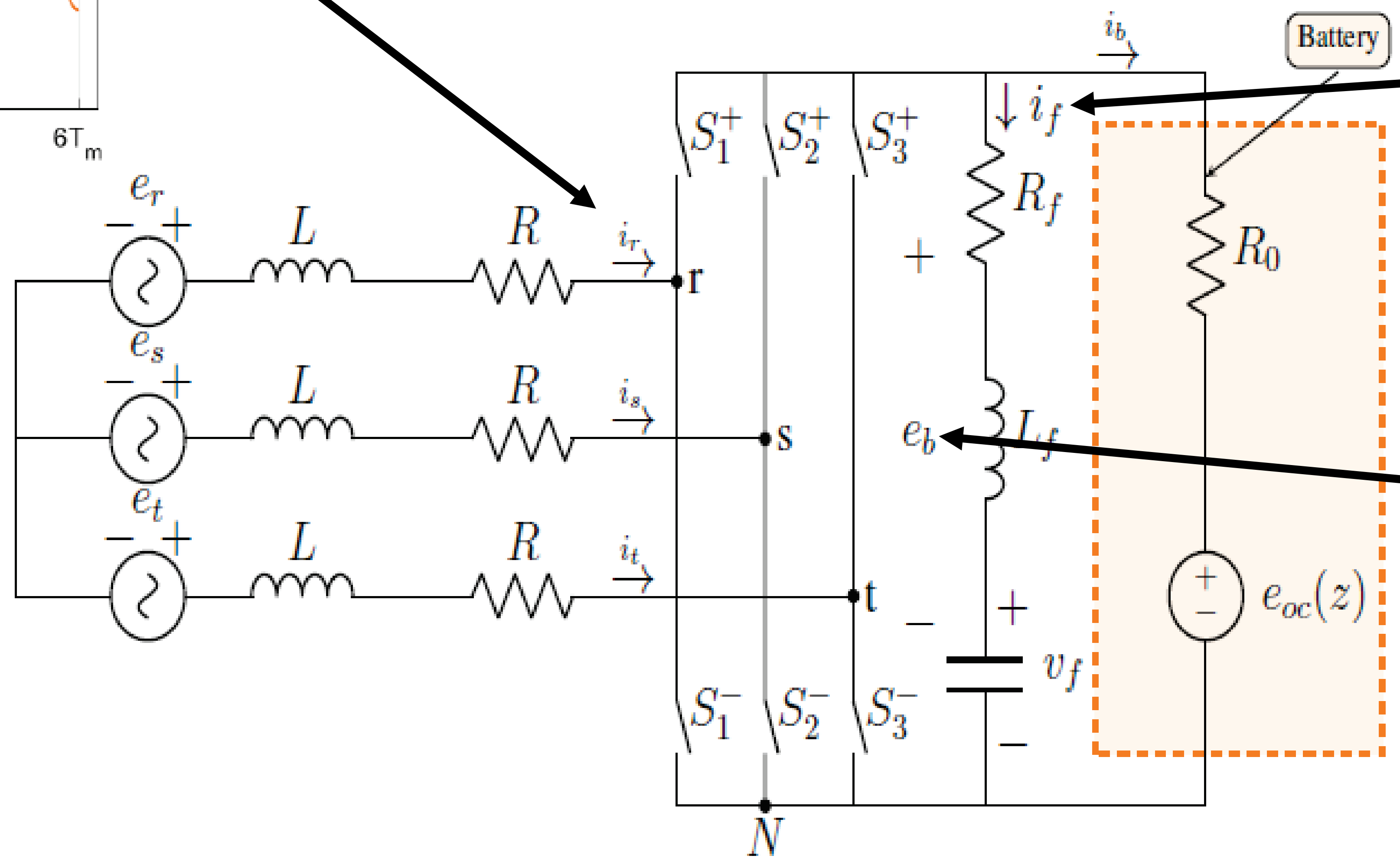
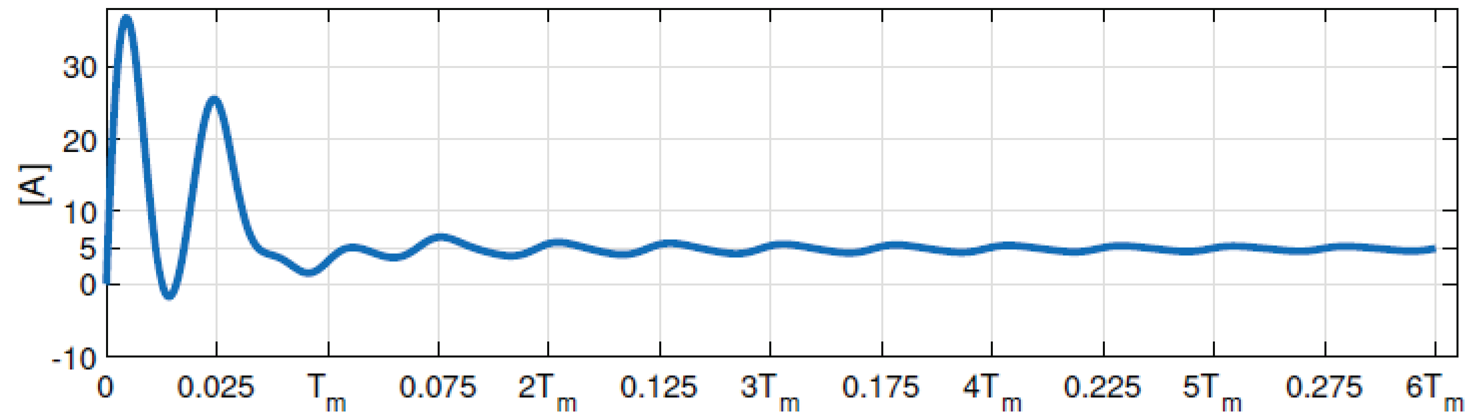
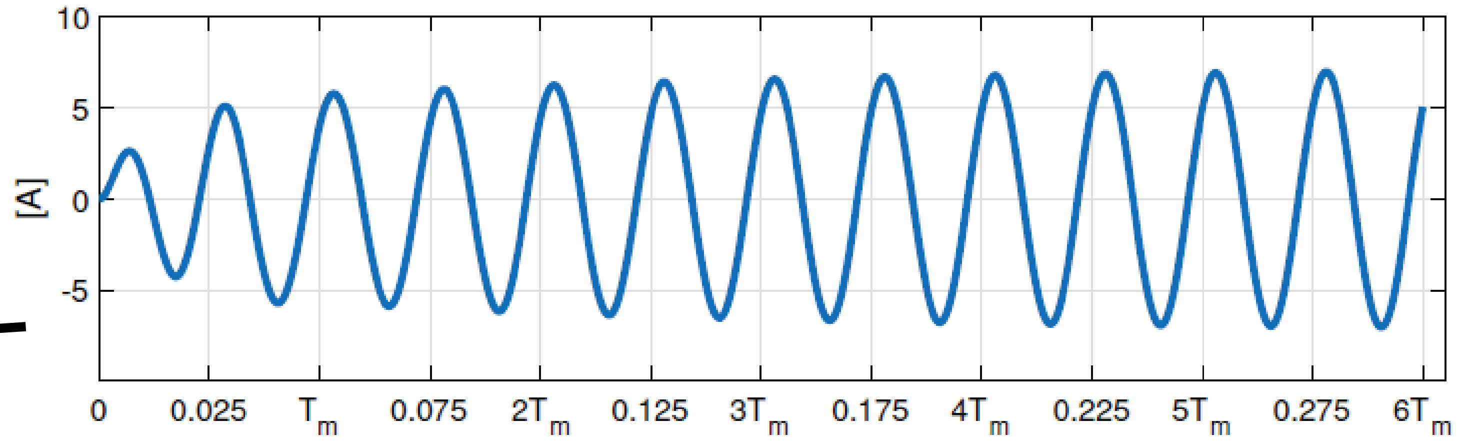


Phases currents i_{rst}

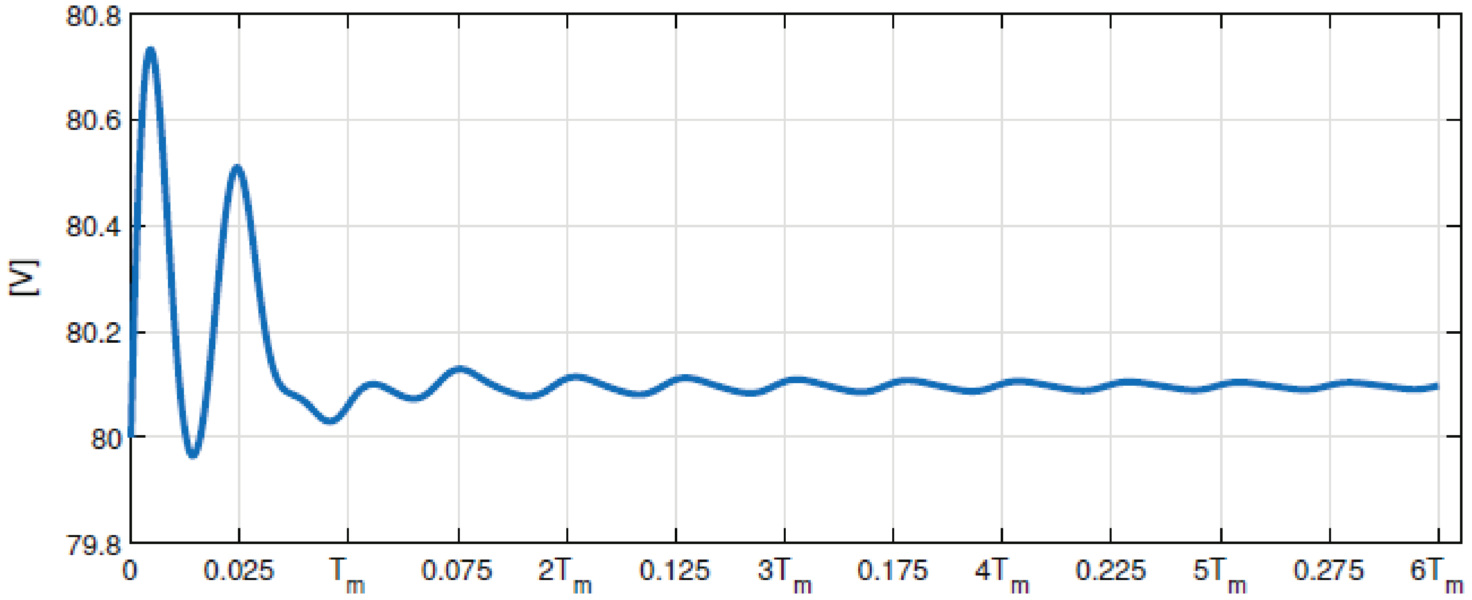




Battery current i_b [s]



Filter current i_f [s]

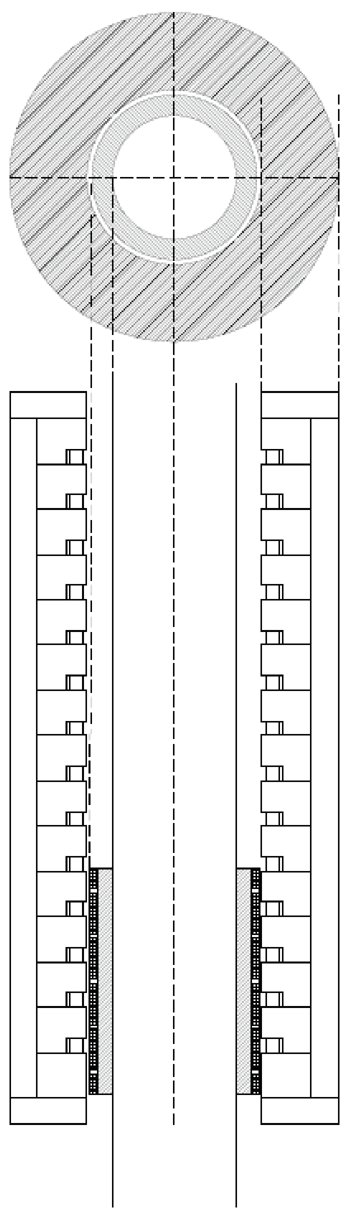


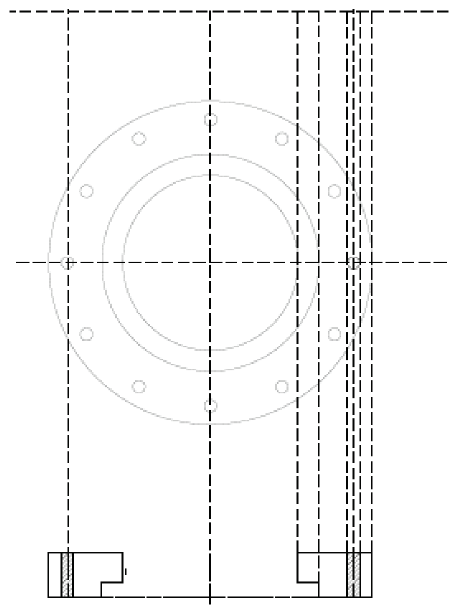
Battery voltage e_b [s]

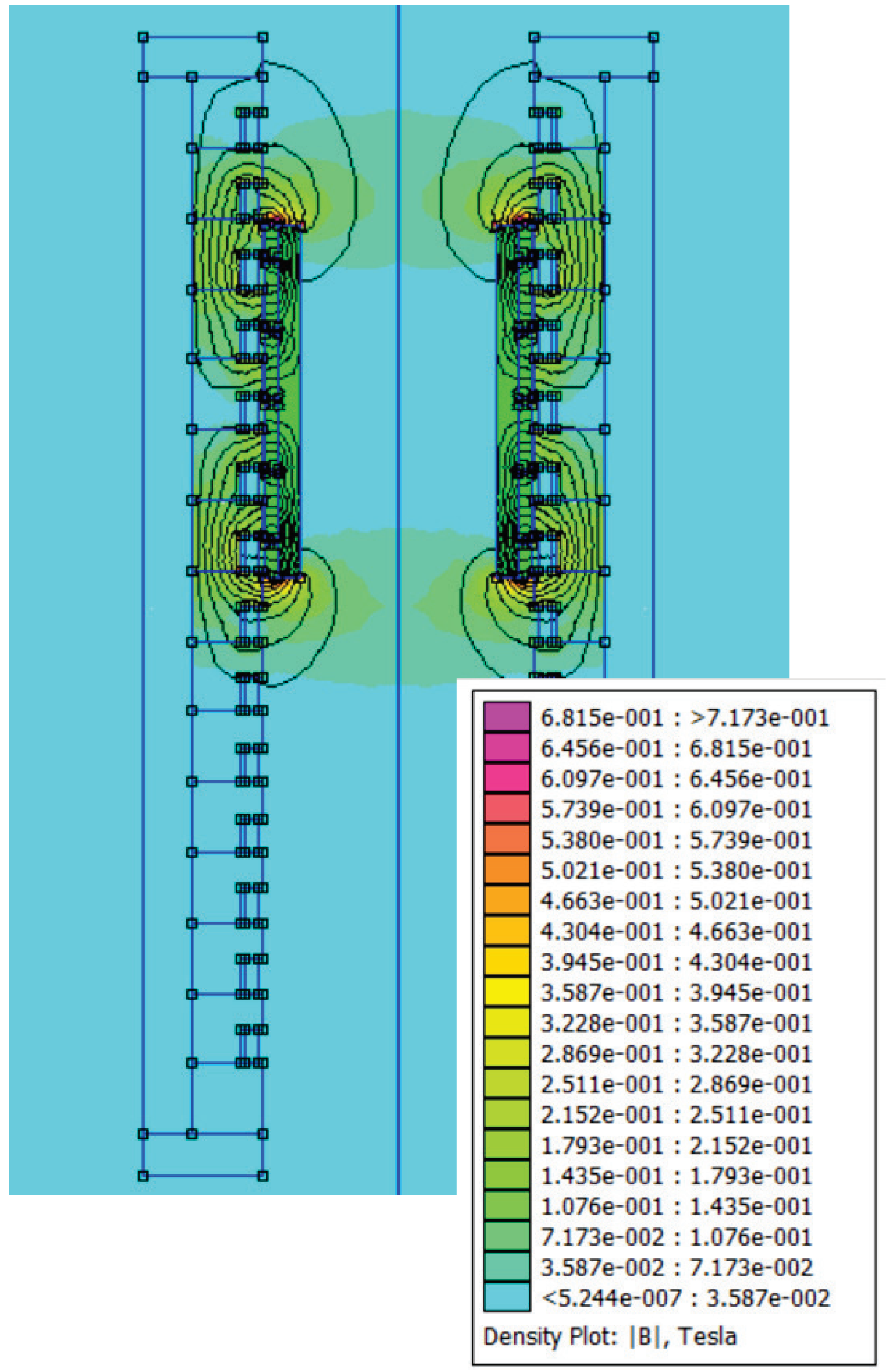
Polyphase FPLG design

- Within the Free-Most a polyphase FPLG is under design

- Flow variation only affects a subset of the coils for each piston position
- Mutual inductance is negligible
- Polyphase configuration is preferred
- Peak efficiency is upper 97%







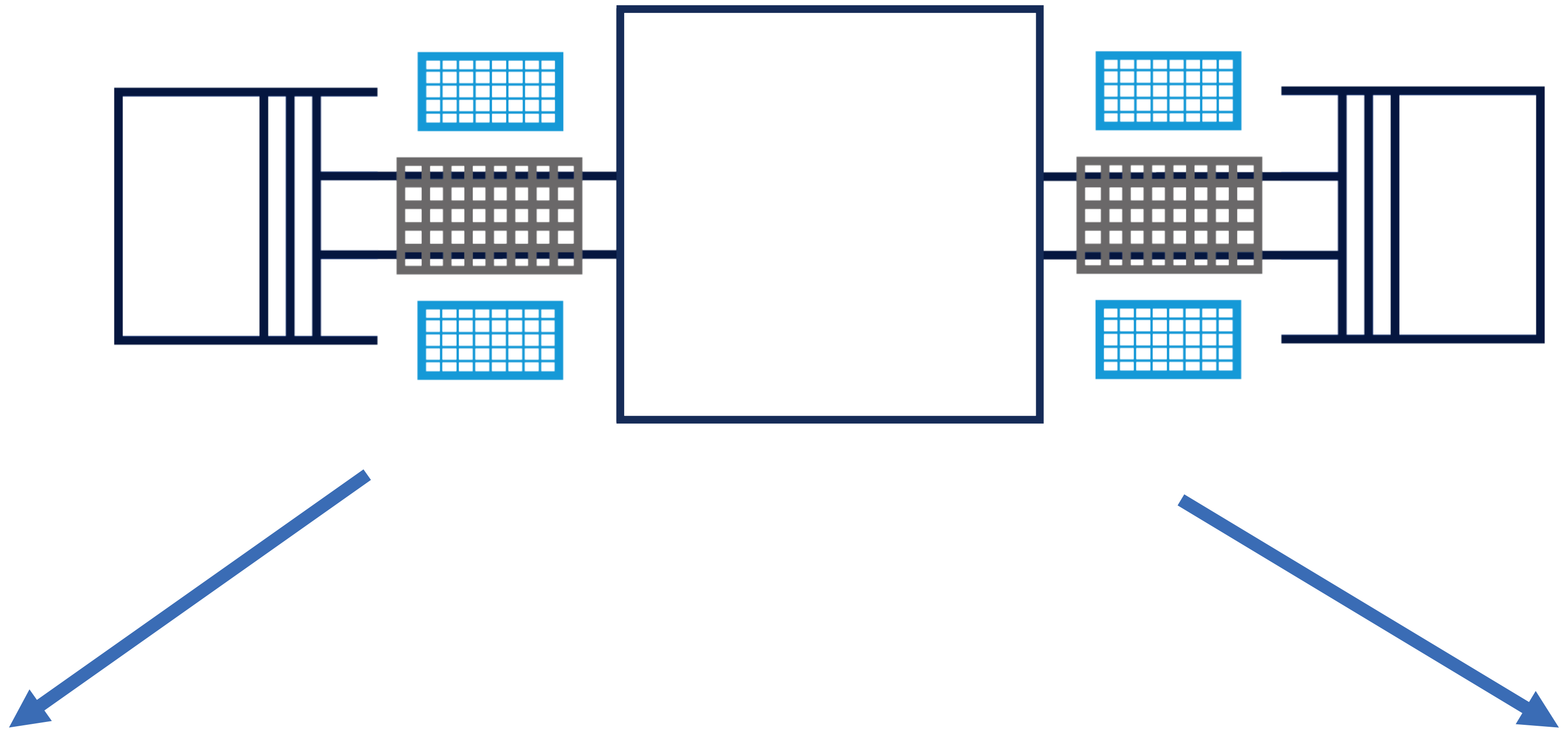
peak Voltage (V)	80
nominal power (kW)	3
COIL	**OK**
coil cross section (mm^2)	3,10
number of turns	14
mean radius (mm)	51,97
copper weight density (kg/m^3)	8960
number of simultaneous active phases	3
mean coil length (cm)	457
Ag (m^2)	2,15E-03
conductor volume (m^3)	1,42E-05
rms voltage (V)	56,6
rms current (A)	17,7
measured resistance N=14 (Ω)	0,0245
measured inductance N=14 (μH)	165
calculated resistance (Ω)	0,0254
calculated inductance (μH)	176
calculated weight (kg)	2,16
coil losses (W)	23,86
total losses (W)	79,41
efficiency	0,974

SLOT	
slot width (mm)	3
height slot (mm)	18,53
Slot area (mm^2)	55,59
STATOR	
stator external radius (mm)	80
stator internal radius (mm)	42,7
height stator (mm)	141
polar pitch (mm)	8
slots number	17
stator losses (W/kg)	4,40924
iron weight density (kg/m^3)	7650
air gap (mm)	1,5
ring area 1 (m^2)	0,01438
ring area 2 (m^2)	0,00833
single ring volume (m^3)	9,7E-05
Stator volume (m^3)	0,00165
utilization index	0,326241135
stator weight (kg)	12,60
stator losses (W)	55,55

Stator material	5	SiFe19
Mover material	4	ULTRAVAC44V6
Magnet	Magnete NeFeBo	
u0	1,25664E-06	
MOVER		
magnets tichness (mm)	4	
magnets height (mm)	10	
magnets spacing (mm)	2	
magnet weight density (kg/m^3)	7600	
magnets external radius (mm)	42,7	
magnets internal radius (mm)	38,7	
magnets volume (m^3)	1,02E-05	
magnet weight (kg)	7,77E-02	
mover height (mm)	46	
mover internal radius (mm)	30	
mover external radius (mm)	38,7	
mover losses (W/kg)	0,25	
mover weight density (kg/m^3)	7870	
mover volume (m^3)	3,48E-06	
mover weight (kg)	2,74E-02	
mover weight without rod (kg)	0,1051	
mover losses (W)	0,0069	

Test rig

- Procurement of the test rig is started and the test rig is under development



- Single linear motor data:
  - 5kW
  - Frequency 5Hz
  - Travel length (one-way): 250 mm
  - Mass: 10 kg
  - Average velocity: 2.45 m/s

- A linear motor is used as motor and controlled in position/velocity
- It emulates the gas expansion

- The second linear motor is used as generator to test the developed controller

Conclusions

- Achievements:
  - Model of the FPLG + Converter + Battery
  - Design of the controller for battery recharging
  - Digital twin development and validation
  - Design of a polyphase linear motor
  - Test rig design and procurement
- Publications:
  - A conference paper accepted
  - A conference paper submitted
- Dissemination:
  - A conference
  - A workshop

Future works

- Increase the power size and the frequency of the test rig
- Modify the developed controller for piston-like expansion motion
- Derive a control system for the piston position
- Extend the control to a polyphase motor
- Evaluate the possibility to consider a supercapacitor in the electrical scheme
- Emulate the combustion through compressed air
- Include combustion