UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

itee PhD information technology electrical engineering

DIETI UNINA

Antonio Di Pasquale

Smart Urban Rail: Power System Modelling and Development of Optimal Centralised Control Strategies

Supervisor: Prof. **Mario Pagano**

Cycle: **XXXVI**

Year: **Third**

BACKGROUND

- M.Sc. in Electrical Engineering – Università degli Studi di Cassino e del Lazio Meridionale
- Research group: Power Systems (ING-IND/33)
- PhD start date: 01/11/2020 (Academic Year 2020-2021)
- Scholarship type: “UNINA”
- Period abroad: Ecolé Polytechnique Fédérale de Lausanne (EPFL), under the supervision of Prof. Mario Paolone (12/09/2022 – 12/12/2022)

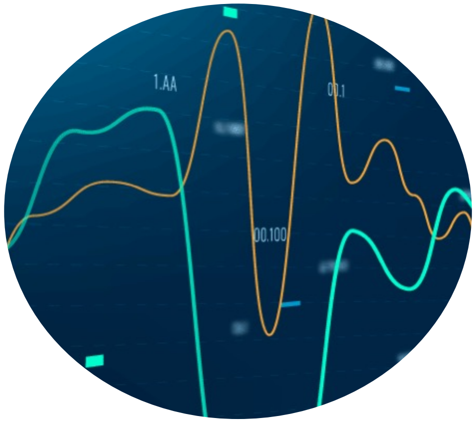
SUMMARY OF STUDY ACTIVITIES

- <u>Ad hoc courses</u>
  - Probability Calculus and Elements of Stochastic Modelling
  - Numerical Treatment of PDEs
  - Scientific Programming and Visualization with Python
  - Matrix Analysis for Signal Processing with MATLAB Examples
  - Operational Research Mathematical Modelling, Methods and Software Tools for Optimization Problems

- <u>PhD Schools</u>
  - European PhD School 2021: Power Electronics, Electrical Machines, Energy Control and Power
  - Ph.D. School F. Gasparini

- <u>Seminars</u>
  - 27 seminars organised by the University of Naples, IEEE and IEEE PELS (Power Electronic Society)

RESEARCH AREAS



Modelling of DC railway systems: investigation and development of steady-state and dynamic models.

Optimal control strategies for urban rail systems: developing strategies for efficient management of urban rail systems.

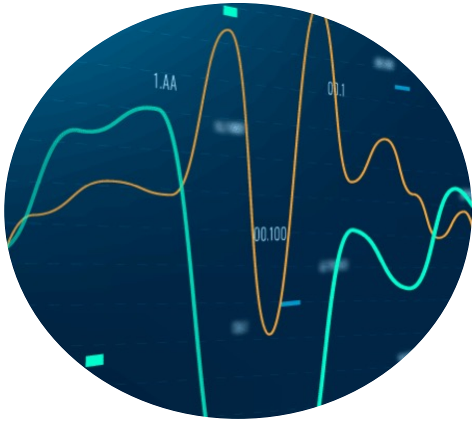
Harmonic power-flow study of polyphase grids with converter-interfaced distributed energy resources: assessing mathematical properties and conditions guaranteeing the existence and uniqueness of solutions for the harmonic power flow problem.

Scheduling algorithms for ultra-fast recharge of plug-in electric vehicles: development of online scheduling algorithms to find optimal ultra-fast charging power profiles for multiple vehicles in the same charging station.

itee PhD information technology electrical engineering

RESEARCH RESULTS

The subject of the thesis. See the following



The existence and uniqueness of the solution are assessed through the Banach–Caccioppoli Theorem.

(Paper under drafting in collaboration with EPFL Research group)

Development of online scheduling algorithms tailored for the infrastructure installed at DIETI

PRODUCTS

[C1]	Amedeo Andreotti, Bianca Caiazzo, Antonio Di Pasquale, Mario Pagano. On Comparing Regressive and Artificial Neural Network Methods for Power System Forecast. *In 2021 AEIT International Annual Conference. (AEIT), 1-6, 2021, IEEE.* Oct 04-08, 2021 Milan, Italy.
[C2]	Pasquale Franzese, Antonio Di Pasquale, Diego Iannuzzi, Mario Pagano. Electric Ultra Fast Charging Stations: a Real Case Study. *In 2021 AEIT International Annual Conference (AEIT), 1-6, 2021, IEEE.* Oct 04-08, 2021 Milan, Italy.
[C3]	Andreotti, A., Di Pasquale, A., Mottola, F., Pagano, M., & Proto, D. (2022, May). Voltage Quality of an AC Grid Supplying a Railway Power System with Energy Saving Strategy. *In 2022 20th International Conference on Harmonics & Quality of Power (ICHQP) (pp. 1-6). IEEE.* May 29 - June 01, 2022 Naples, Italy.
[C4]	Emanuele Fedele, Antonio Di Pasquale, Diego Iannuzzi, Mario Pagano. Integration of Onboard Batteries and Supercapacitors Based on the Multi-Source Inverter for Light Rail Vehicles. *In 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 698-704, 2022, IEEE.* May 15 – 19, 2022 Himeji, Japan.
[C5]	Antonio Di Pasquale, Emanuele Fedele, Diego Iannuzzi, Mario Pagano. Contribution of Wayside Energy Storage Systems to Short Circuit Currents in DC Railway Traction Power Systems. *In 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 1101-1106, 2022, IEEE.* May 15 – 19, 2022 Himeji, Japan.

PRODUCTS

[C6]	Amedeo Andreotti, Antonio Di Pasquale, Mario Pagano, Nagananthini Ravichandran, Francesco Volpe. An Optimal Centralized Control Strategy for Regenerative Braking Energy Flow Exchanges in DC Railway Traction Systems. *In 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 436-441, 2022, IEEE.* June 22 – 24, 2022 Sorrento, Italy.
[C7]	Antonio Di Pasquale, Mario Pagano, Carlo Petrarca, Francesco Volpe. Assessing a Health Index Algorithm for High Voltage Overhead Power Lines. *In 2022 AEIT International Annual Conference (AEIT), 1-6, 2022,* IEEE. Oct 03 – 05, 2022 Rome, Italy.
[C8]	Amedeo Andreotti, Antonio Di Pasquale, Mario Pagano, Nagananthini Ravichandran, Francesco Volpe. Analysis of Lightning Transients in 2x25 kV 50 Hz Railway Traction System using EMTP. *In 2022 AEIT International Annual Conference (AEIT), 1-6, 2022, IEEE.* IEEE. Oct 03 – 05, 2022 Rome, Italy.
[C9]	Ciro Attaianese, Antonio Di Pasquale, Emanuele Fedele, Diego Iannuzzi, Mario Pagano, Mattia Ribera. Energy Efficiency Assessment for an Ultra-Fast Charging Station. *In 2022 IEEE Vehicle Power and Propulsion Conference (VPPC), 1-7, 2022, IEEE.* Nov 01-04, 2022 Merced, CA, USA.
[C10]	Nagananthini Ravichandran, Amedeo Andreotti, Mario Pagano, Antonio Di Pasquale, Francesco Volpe. Interconnection Topologies for Floating Photovoltaic System to Enhance the Power Output by Reducing the Mismatch Losses. *In 2022 IEEE PES 14th Asia-Pacific Power and Energy Engineering Conference (APPEEC), 1-6, 2022, IEEE.* Nov. 20 – 23, 2022, Melbourne, Australia.

PRODUCTS

[C11]	Antonio Di Pasquale, Mario Pagano, Fabio Villone, Antonio Martinelli, Luigi Rufolo, Maurizio Santamaria, Francesco Vaccaro. Modelling and Determination of Short Circuit Traction Line Parameters for the Italian 3 kV DC Railway System. *In 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), 1-6, 2023, IEEE.* March 29 – 31, Venice, Italy.
[C12]	Antonio Di Pasquale, Emanuele Fedele, Diego Iannuzzi, Mario Pagano. Centralised Control Strategy for an Urban Rail Network in the Presence of Onboard Storage Systems. *In 2023 AEIT International Annual Conference (AEIT).* Oct 05 – 07, 2023 Rome, Italy.
[C13]	Nagananthini Ravichandran, Amedeo Andreotti, Antonio Di Pasquale, Mario Pagano, Daniela Proto, Erika Stracqualursi, Rodolfo Araneo, Luigi D'Orazio. Selection of Viable Distribution Line Surge Arrester for Prospective Optimal Protection. *In 2023 AEIT International Annual Conference (AEIT).* Oct 05 – 07, 2023 Rome, Italy.
[J1]	Marilisa Botte, Luca D'Acierno, Antonio Di Pasquale, Fabio Mottola, Mario Pagano. Optimal motion of a rolling stock fleet under traction power system constraints. *In IEEE Transactions on Transportation Electrification, 9(1), 1554-1563, 2022, IEEE.*
[J2]	Ciro Attaianese, Antonio Di Pasquale, Pasquale Franzese, Diego Iannuzzi, Mario Pagano, Mattia Ribera. A model-based EVs charging scheduling for a multi-slot Ultra-Fast Charging Station. *In Electric Power Systems Research, 216, 109009, 2023, Elsevier.*
[J3]	Marilisa Botte, Luca D'Acierno, Antonio Di Pasquale, Fabio Mottola, Mario Pagano. Optimal Allocation of Layover Time in a Smart DC Railway Metro Traction System. *In IEEE Transactions on Vehicular Technology.* (**Accepted**)

THESIS OVERVIEW

The world's population is **8 billion**, projected to reach **10 billion** by 2050, with urbanization increasing from 55% to 70%. This growth will boost urban transport demand **(60-90%)**.

Without adequate response from policies, planners, and operators, it will harm people's quality of life and social welfare due to heavy reliance on polluting road transport.

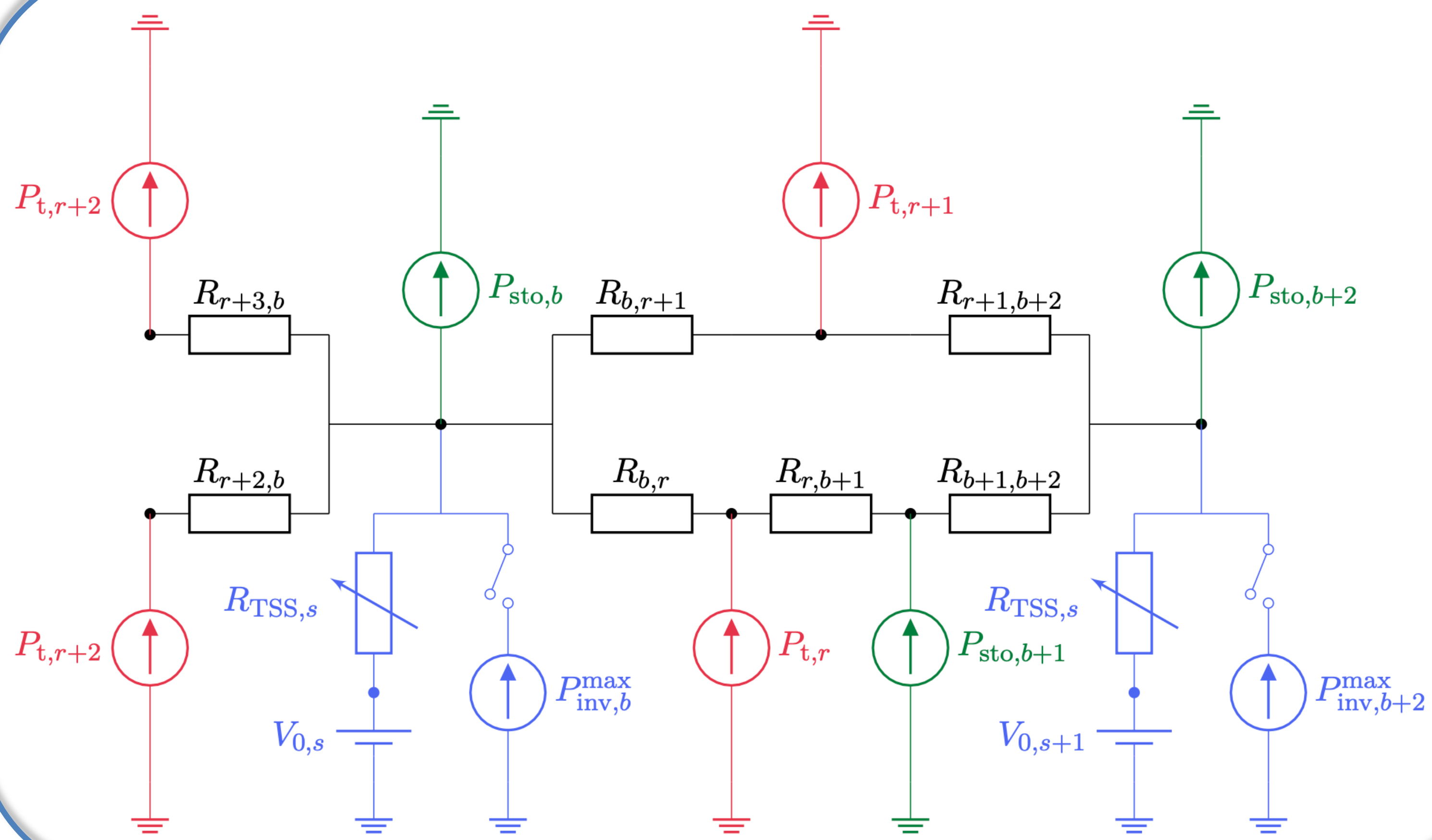
In this context, **sustainable trasport** plays a crucial role, as promotes better integration of the economy while respecting the environment

Therefore, the thesis work aims to propose a cost-effective and less time-demanding solution to reduce energy consumption in urban rail systems, based on a **centralised control paradigm**.

PHD THESIS

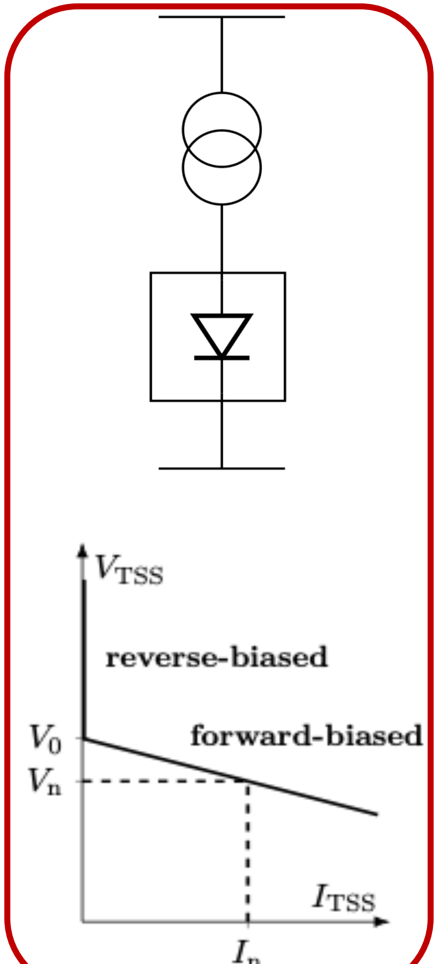
- Scientific Proposal:
  - An **in-depth study of the railway system steady-state modelling**, tailored for the power flow investigations. Particular attention has been dedicated to modelling the **limited network receptivity** and the **loss of the slack bus**, which can occur due to simultaneous power injection from braking trains.
  - The thesis proposes multiple **centralised control strategies**, each tailored for different configurations of traction systems. All these strategies are framed as Optimal Traction Power Flows, which aim to reduce the energy supplied by the substations while maintaining the quality of service, even in the event of an increase in transportation demand.
- Originality:
  - W.r.t. the existing literature a **more extensive model** of the traction system is provided.
  - A **new approach** to address the **limited receptivity** of the network and the **loss of the slack bus** is proposed.
  - The **centralised control paradigm** for railway systems is underexplored. New control strategies are proposed.

DC URBAN RAIL MODEL

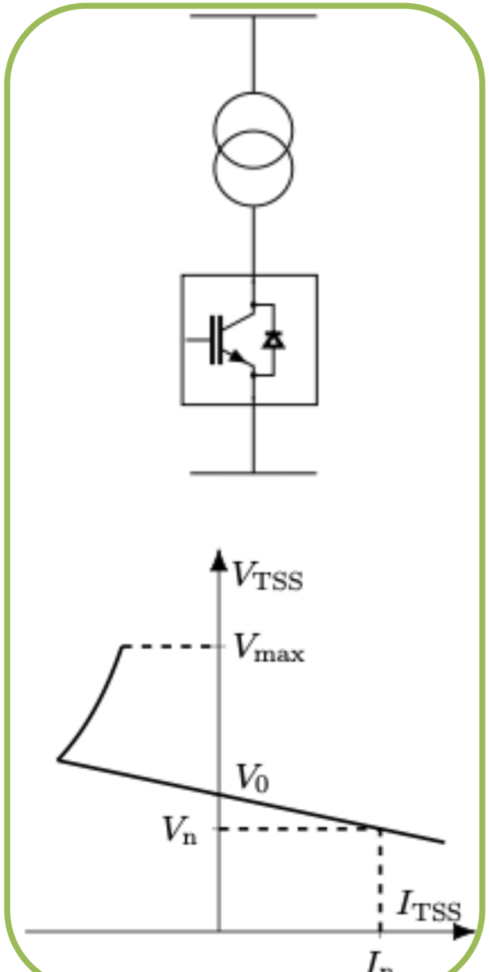


MODEL LIBRARY: TRACTION SUBSTATION

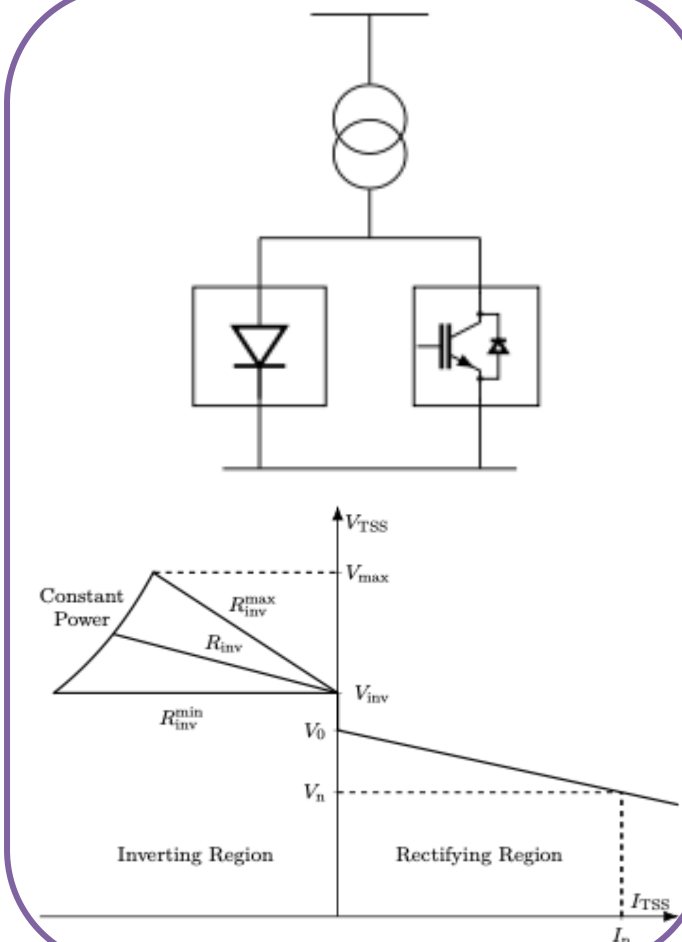
Diode-based



IGBT-based

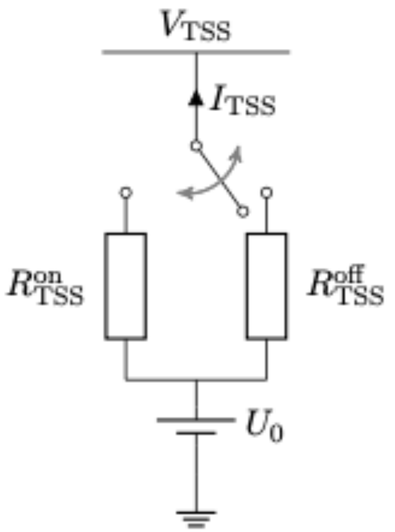


Hybrid (Diode+IGBT)

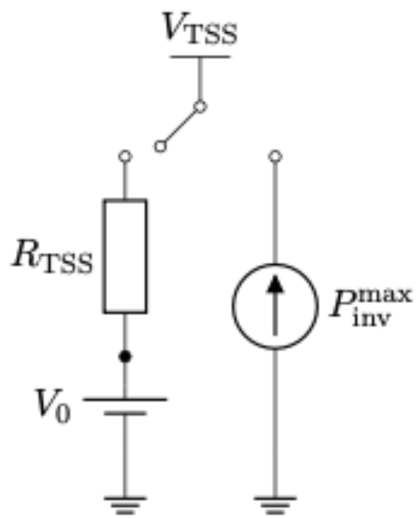


MODEL LIBRARY:
TRACTION SUBSTATION EQUIVALENT MODE

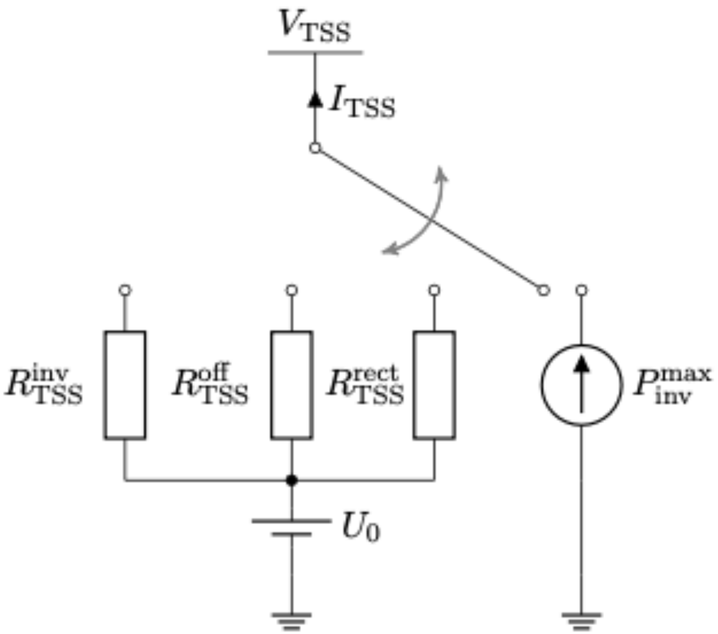
Diode-based



IGBT-based

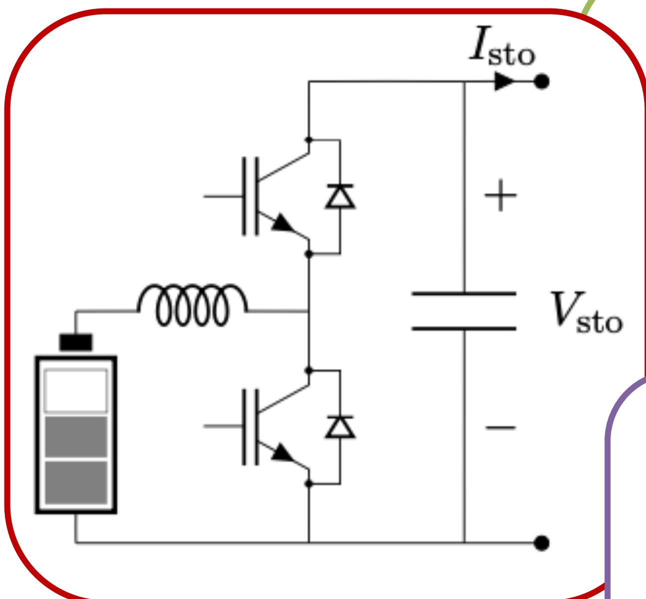


Hybrid (Diode+IGBT)

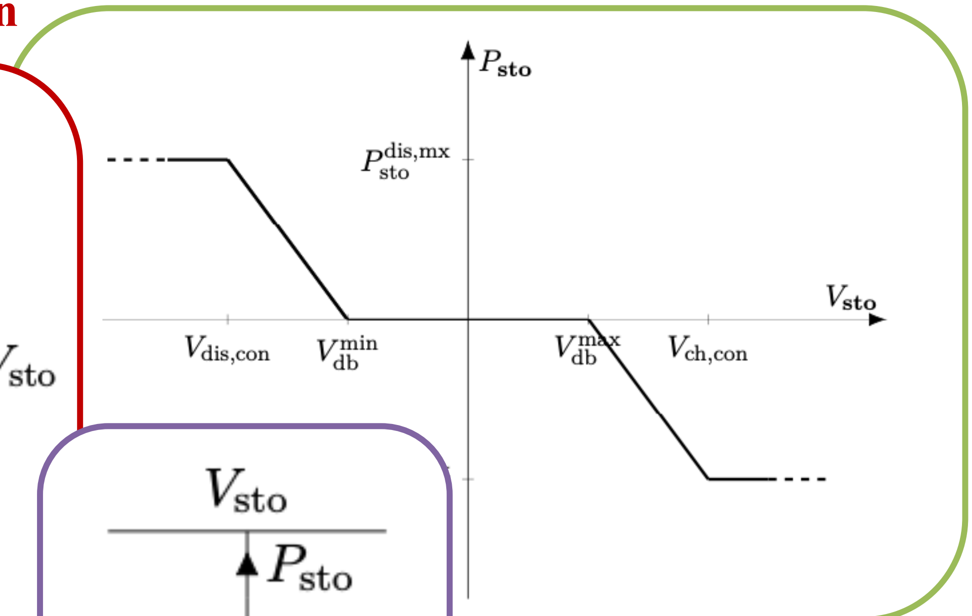


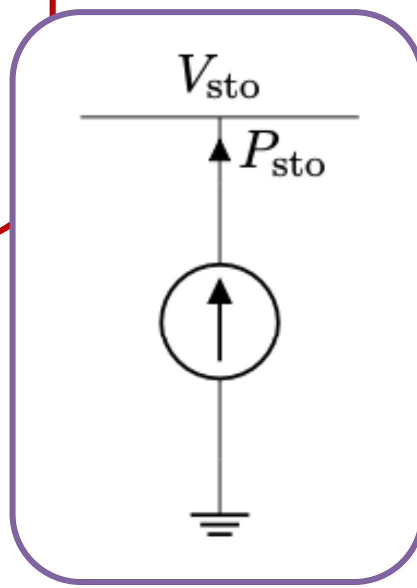
MODEL LIBRARY: WAYSIDE STORAGE SYSTEM

Schematic Representation



Operating Characteristic

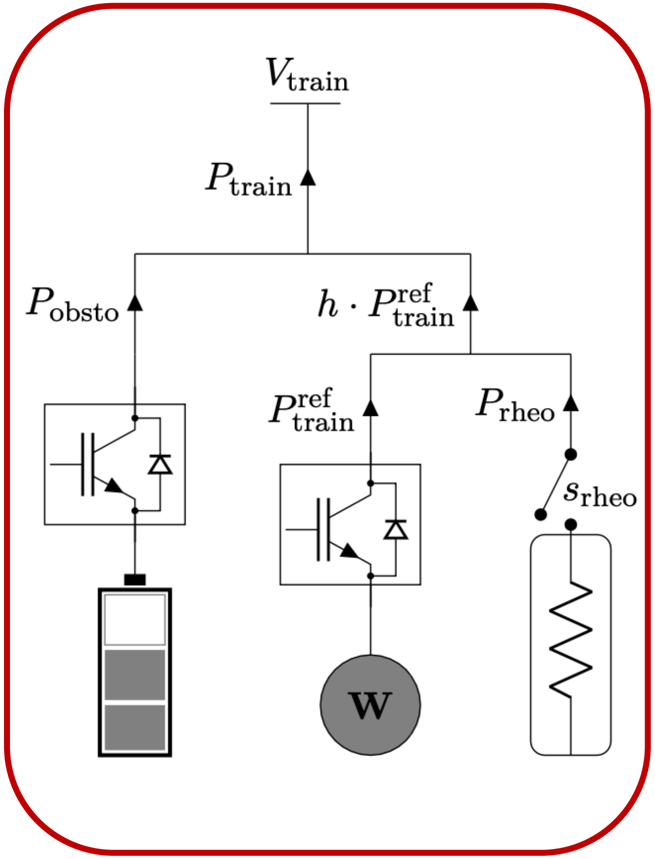




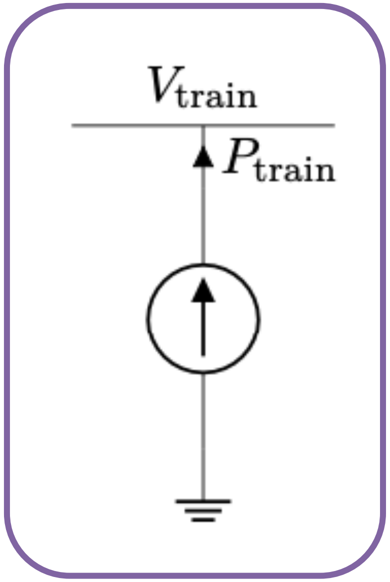
Equivalent Circuit

MODEL LIBRARY: TRAIN

Schematic Representation



Equivalent Circuit



TRACTION POWER FLOW

S: set of substations
B: set of wayside storage systems
R: set of trains

Nodal Voltage

$$\text{diag}\left\{\begin{bmatrix}\mathbf{V}_{\mathcal{S}}\\ \mathbf{V}_{\mathcal{B}}\\ \mathbf{V}_{\mathcal{R}}\end{bmatrix}\right\}\begin{bmatrix}\mathbf{G}_{\mathcal{S}\times\mathcal{S}} & \mathbf{G}_{\mathcal{S}\times\mathcal{B}} & \mathbf{G}_{\mathcal{S}\times\mathcal{R}}\\ \mathbf{G}_{\mathcal{B}\times\mathcal{S}} & \mathbf{G}_{\mathcal{B}\times\mathcal{B}} & \mathbf{G}_{\mathcal{B}\times\mathcal{R}}\\ \mathbf{G}_{\mathcal{R}\times\mathcal{S}} & \mathbf{G}_{\mathcal{R}\times\mathcal{B}} & \mathbf{G}_{\mathcal{R}\times\mathcal{R}}\end{bmatrix}\begin{bmatrix}\mathbf{V}_{\mathcal{S}}\\ \mathbf{V}_{\mathcal{B}}\\ \mathbf{V}_{\mathcal{R}}\end{bmatrix}=\begin{bmatrix}\mathbf{P}_{\mathcal{S}}\\ \mathbf{P}_{\mathcal{B}}\\ \mathbf{P}_{\mathcal{R}}\end{bmatrix}$$

Nodal Power

Conductance Matrix

The power flow in traction systems is a nonlinear problem involving the determination of nodal voltages and power values to satisfy the power flow equations (i.e., **F** = 0):

$$\Gamma_{\text{PF}}=\{(\mathbf{V}_{\mathcal{S}},\mathbf{V}_{\mathcal{B}},\mathbf{V}_{\mathcal{R}},\mathbf{P}_{\mathcal{S}},\mathbf{P}_{\mathcal{B}},\mathbf{P}_{\mathcal{R}})\mid\mathbf{F}=0\}$$

LIMITED NETWORK RECEPTIVITY

The receptivity of a traction network indicates its ability to recover regenerative braking energy. However, this process is constrained by the maximum allowable catenary voltage values, beyond which recovery is not possible. Therefore, the surplus of regenerative energy is wasted through the rheostatic braking system.

Taking into account this behaviour in traction power flow is challenging.
Jabr and Dzafic in [1] suggest a matrix-based approach for a different traction power flow formulation.

[1] Rabih A Jabr and Izudin Džafić. Solution of dc railway traction power flow systems including limited network receptivity. *IEEE Transactions on Power Systems*, 33(1):962–969, 2017.

LIMITED NETWORK RECEPTIVITY: SENSITIVITY MATRIX APPROACH

Specifically designed for the traction power flow model proposed in this work!

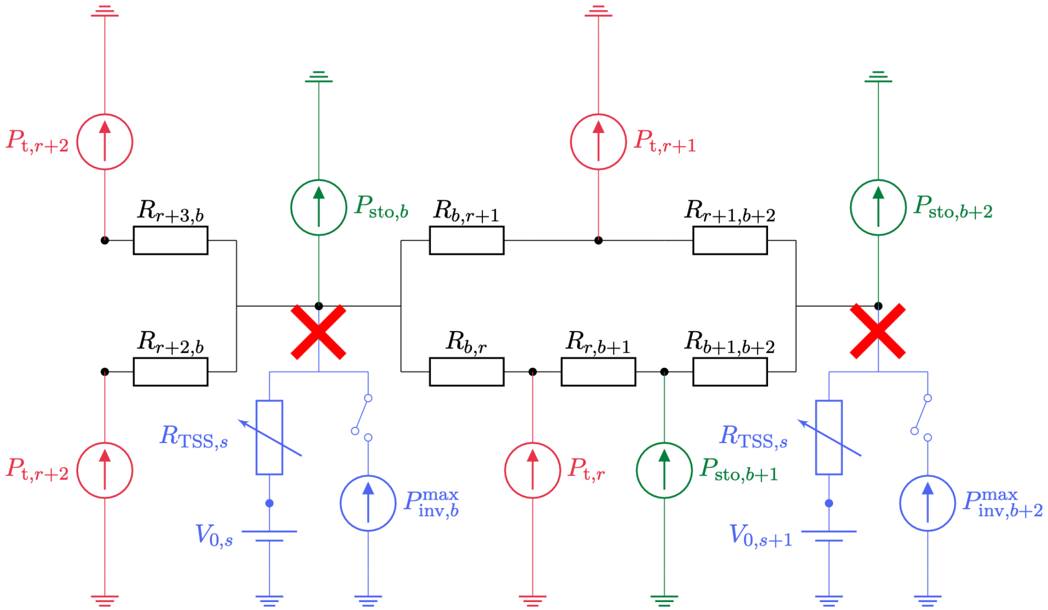
Algorithm 1: Matrix sensitivity traction power flow

Initialisation:
Set counter $k = 1$; Assign train reference power;
Traction power flow calculation:
Solve the traction power flow using the current value of train power to get
$\mathbf{\Gamma}^k_{\mathrm{PF}} = \left(\mathbf{V}^k_{\mathcal{S}}, \mathbf{V}^k_{\mathcal{R}}, \mathbf{V}^k_{\mathcal{B}}, \mathbf{P}^k_{\mathcal{S}}, \mathbf{P}^k_{\mathcal{B}}, \mathbf{P}^k_{\mathcal{R}}\right)$
Stopping criterion check:
Check if any train voltage exceeds the prescribed limits. If not, **exit** ;
Start matrix sensitivity analysis:
Collect trains with over-voltage and compute the sensitivity matrix $\mathbf{H}^k$;
Update train power: $\mathbf{P}^{k+1}_{\mathcal{R}} = \mathbf{P}^k_{\mathcal{R}} + \mathbf{H}^k \cdot \mathbf{\Delta V}_{\mathcal{R}}{}^k$;
Update the counter $k = k + 1$;
Go to Step **Traction power flow calculation**.
return $\mathbf{P}^{(k)}_{\mathcal{R}}$

LOSS OF SLACK BUS

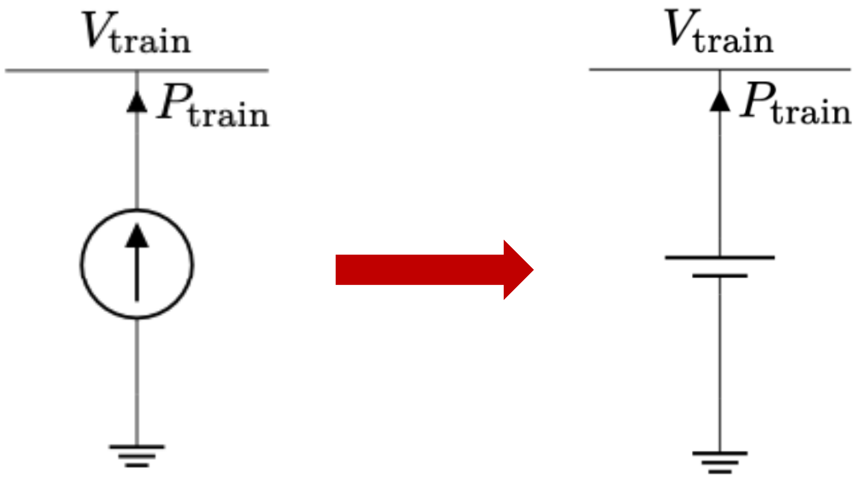
The simultaneous injection of regenerative power by braking trains may lead to having all diode-based substations reverse-biased. In this case, the power flow solution with all the trains modelled as current sources cannot be reliably completed, due to the absence of any slack power source, which fixes a reference for the voltages.

This numerical problem is poorly investigated in the literature.



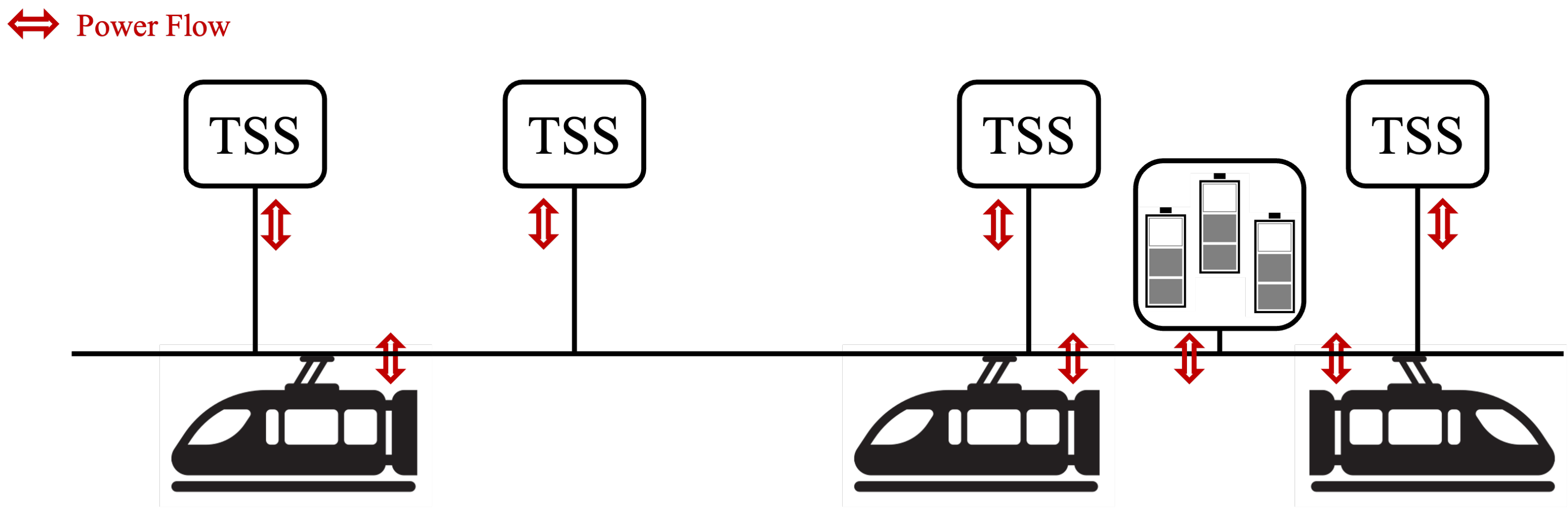
LOSS OF SLACK BUS: SENSITIVITY MATRIX APPROACH

The regenerative train model changes from an ideal **current source** to an ideal **voltage source**, whose value is adjusted through a sensitivity matrix approach.



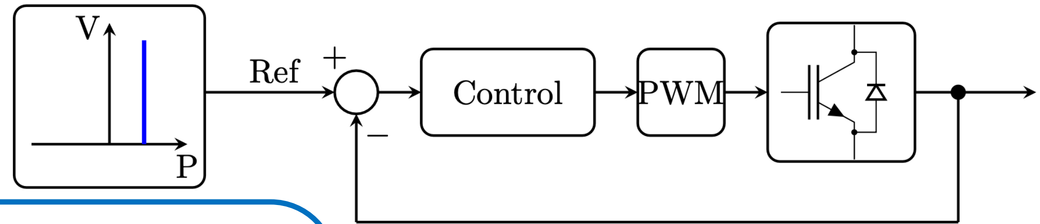
$$\mathbf{\Delta V}^k_{\mathcal{R}_{\text{op}}} = \mathbf{H}^k_{\mathcal{R}_{\text{op}}} \cdot \mathbf{\Delta P}^k_{\mathcal{R}_{\text{op}}}$$

LOCAL CONTROL STRATEGY



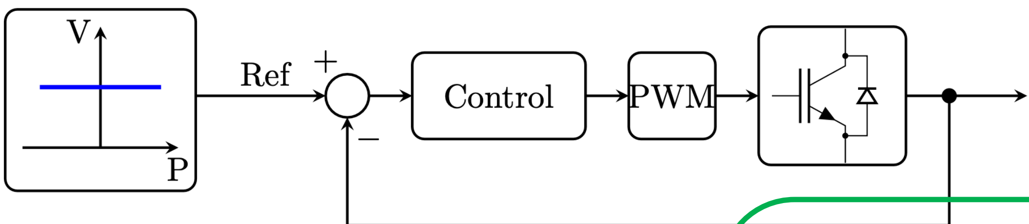
LOCAL CONTROL STRATEGY

Grid-Following

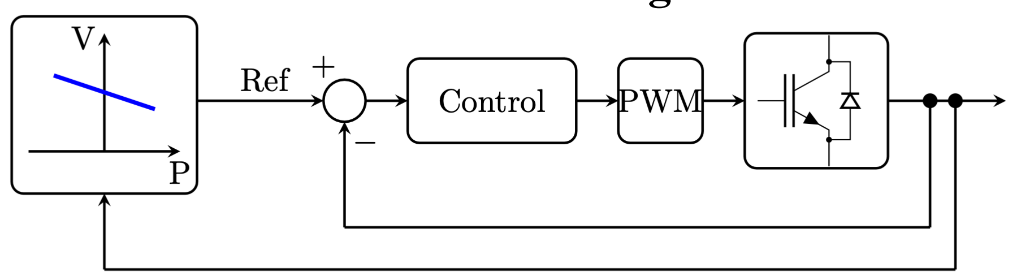


- Trains
- Wayside Storage Systems

Grid-Forming

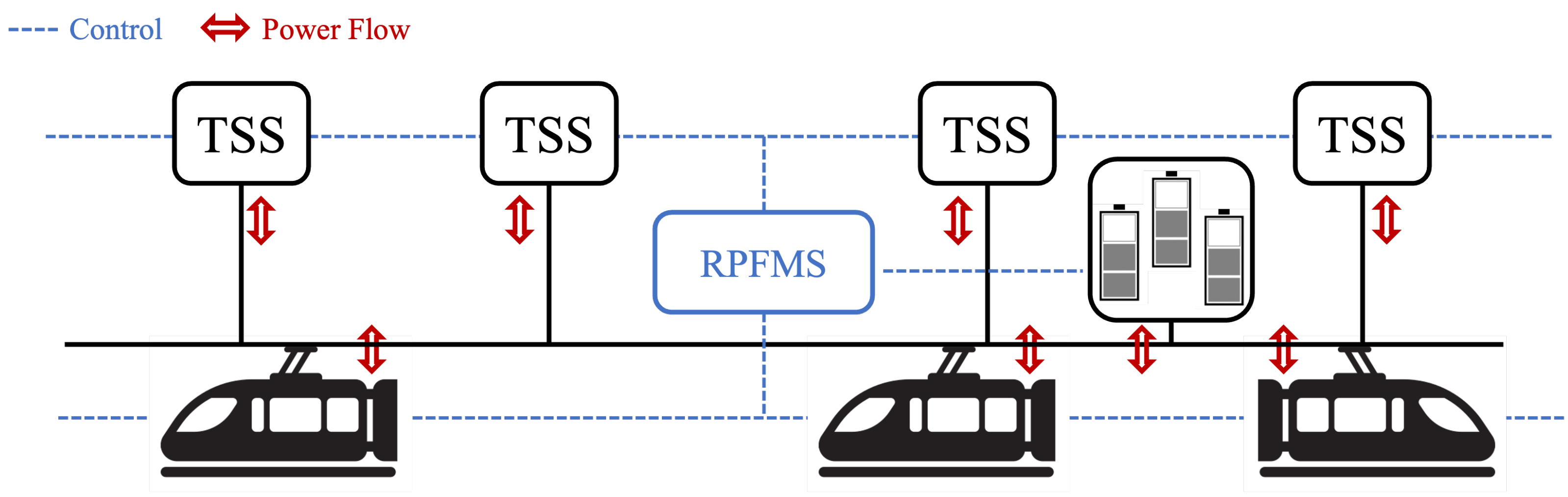


Droop-Controlled Grid-Following

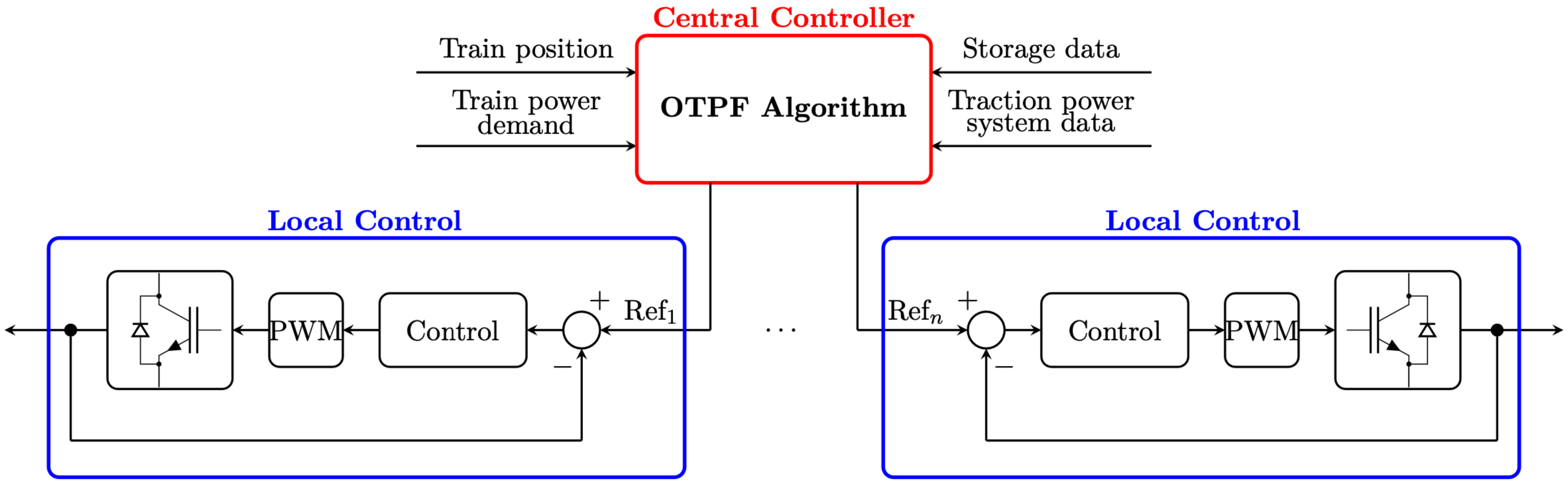


- Traction Substations

CENTRALISED CONTROL PARADIGM



CENTRALISED CONTROL PARADIGM



OPTIMAL TRACTION POWER FLOW

$$\hat{\mathbf{\Gamma}}_{\mathrm{OTPF}} = \arg\min f(\mathbf{\Gamma}_{\mathrm{OTPF}})$$

$$\hat{\mathbf{\Gamma}}_{\mathrm{OTPF}} = \left\{\hat{\mathbf{V}}_{\mathcal{S}}, \hat{\mathbf{V}}_{\mathcal{B}}, \hat{\mathbf{V}}_{\mathcal{R}}, \hat{\mathbf{P}}_{\mathcal{S}}, \hat{\mathbf{P}}_{\mathcal{B}}, \hat{\mathbf{P}}_{\mathcal{R}}\right\}$$

s.t.

$$\mathbf{F} = \mathbf{0}$$
Power flow equations

$$\mathbf{V}_{\mathcal{S}} = \mathbf{V}_0$$
Substation voltage

$$\mathbf{P}_{\mathcal{B}} = \mathbf{0}$$
Wayside storage power

$$\mathbf{P}_{\mathcal{R}}^{\mathrm{ref}} + \mathbf{P}_{\mathrm{obsto}} + \mathbf{P}_{\mathrm{rheo}} - \mathbf{P}_{\mathcal{R}} = \mathbf{0}$$
Train power

$$P_{\mathrm{rheo},r} = 0 \quad \text{if} \quad P_r \leq 0 \quad \forall r \in \mathcal{R}$$
$$\mathbf{P}_{\mathrm{rheo}} \leq \mathbf{0}$$
Rheostatic power

$$\mathbf{P}_{\mathcal{S}} \leq \mathbf{P}_{\mathcal{S}}^{\max}$$
Substation power

$$\mathbf{P}_{\mathrm{obsto}}^{\mathrm{ch,av}} \leq \mathbf{P}_{\mathrm{obsto}} \leq \mathbf{P}_{\mathrm{obsto}}^{\mathrm{dis,av}}$$
Onboard storage power

$$\mathbf{V}_{\mathcal{R}}^{\min} \leq \mathbf{V}_{\mathcal{R}} \leq \mathbf{V}_{\mathcal{R}}^{\max}$$
Train power

OPTIMAL TRACTION POWER FLOW: OBJECTIVE FUNCTION

$$\hat{\boldsymbol{\Gamma}}_{\text{OTPF}} = \arg\min \mathbf{P}_{\mathcal{S}}^{T}\mathbf{P}_{\mathcal{S}}$$

Minimisation of traction substations' power: suitable for unidirectional substations, in the absence of storage devices

$$\hat{\boldsymbol{\Gamma}}_{\text{OTPF}} = \arg\min \mathbf{P}_{\text{rheo}}^{T}\mathbf{P}_{\text{rheo}}$$

Minimisation of rheostatic braking power: suitable for unidirectional substations, in the presence of storage devices

$$\hat{\boldsymbol{\Gamma}}_{\text{OTPF}} = \arg\min \sum_{s\in\mathcal{S}} P_s$$

Minimisation of overall system power: suitable for reversible substations

CENTRALISED CONTROL STRATEGIES

<u>Strategy 1</u>: without energy storge systems

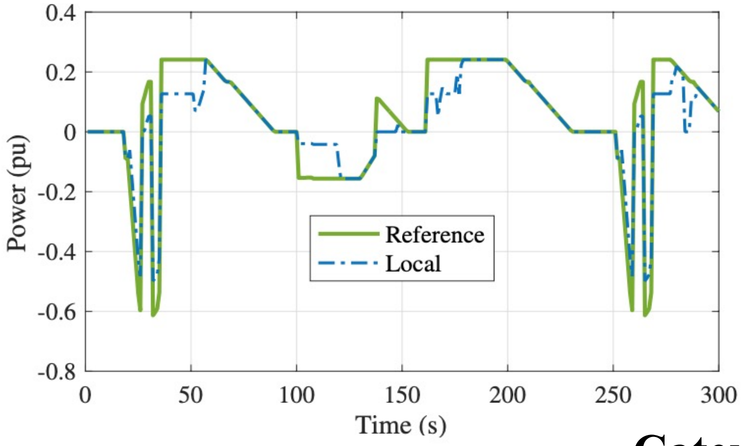
<u>Strategy 2</u>: with onboard storage systems

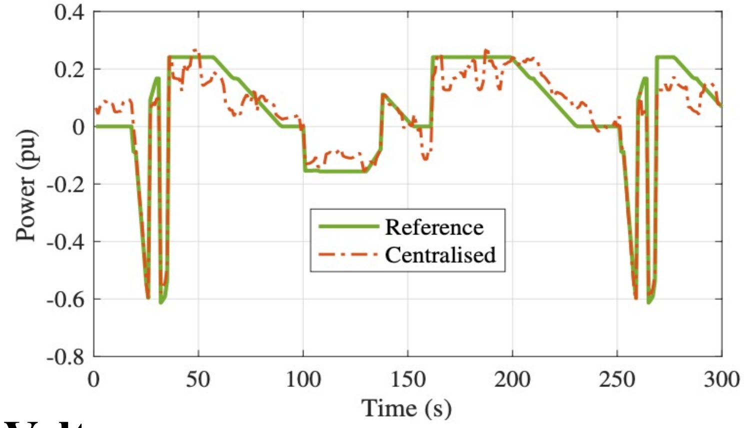
<u>Strategy 3</u>: wayside storage systems

<u>Strategy 4</u>: reversible traction substations

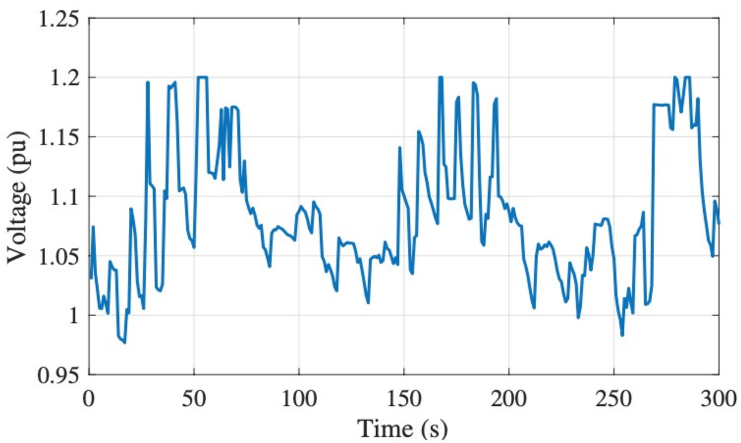
AN EXAMPLE: STRATEGY 2

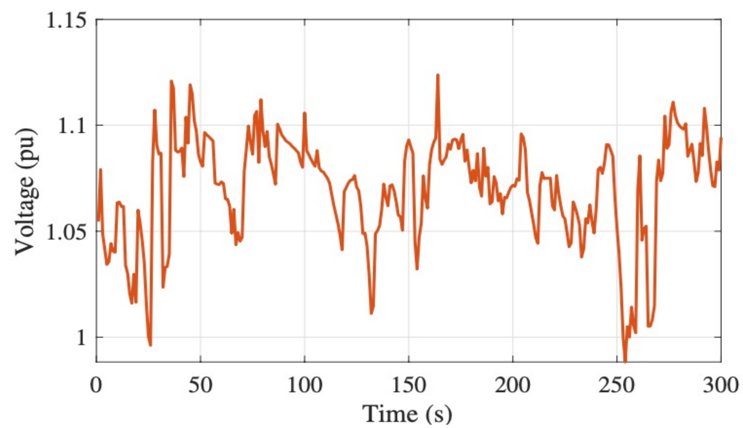
Catenary Power





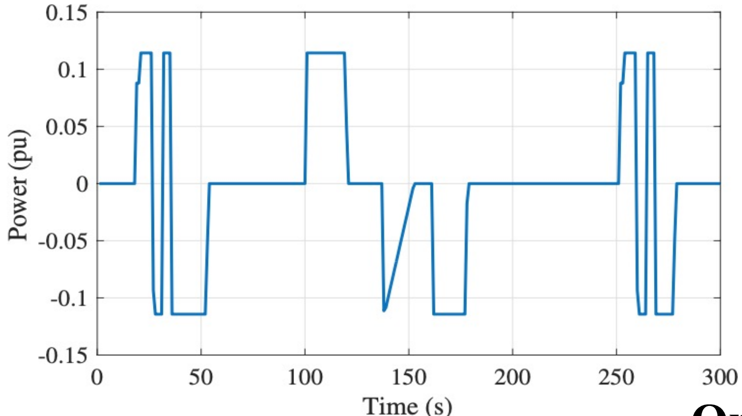
Catenary Voltage

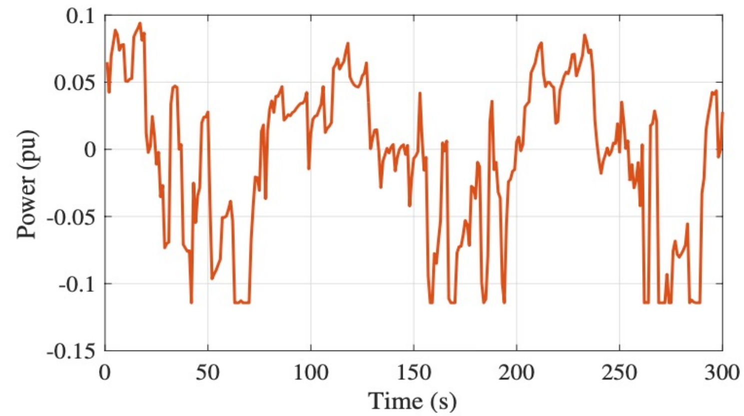




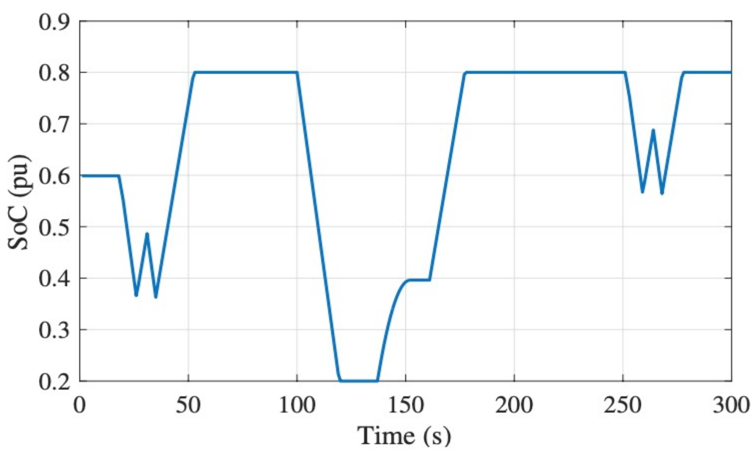
AN EXAMPLE: STRATEGY 2

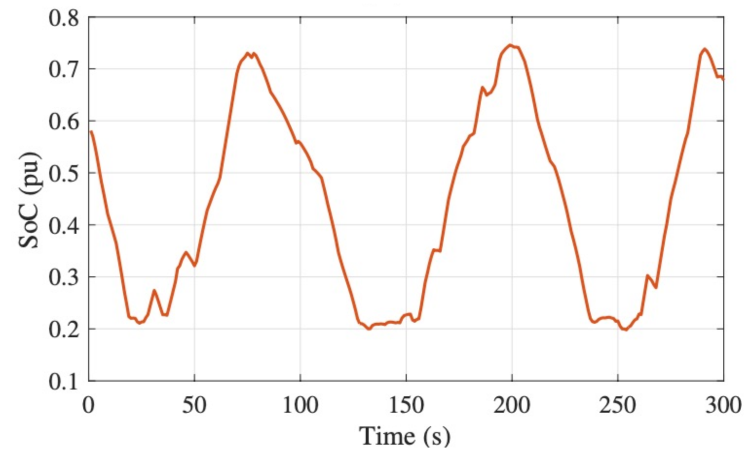
Onboard Power



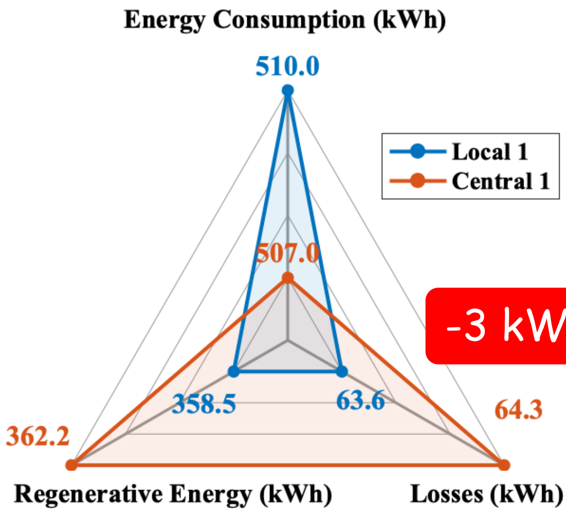


Onboard SoC

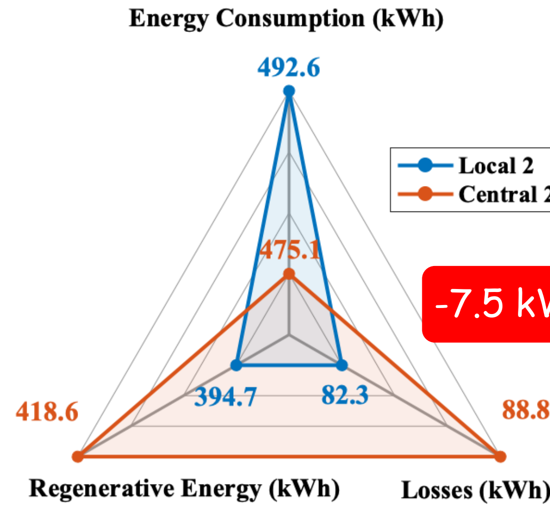




NUMERICAL RESULTS

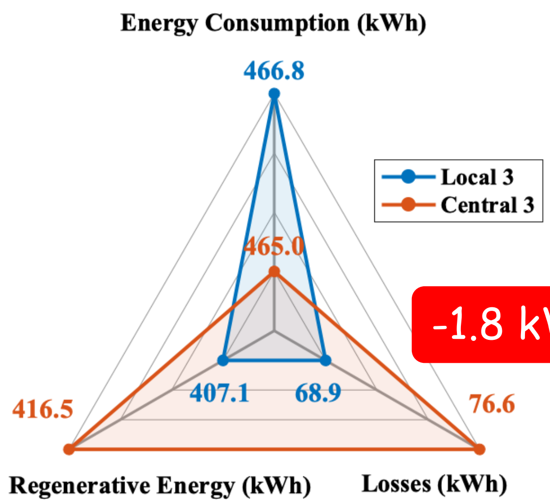


-3 kWh

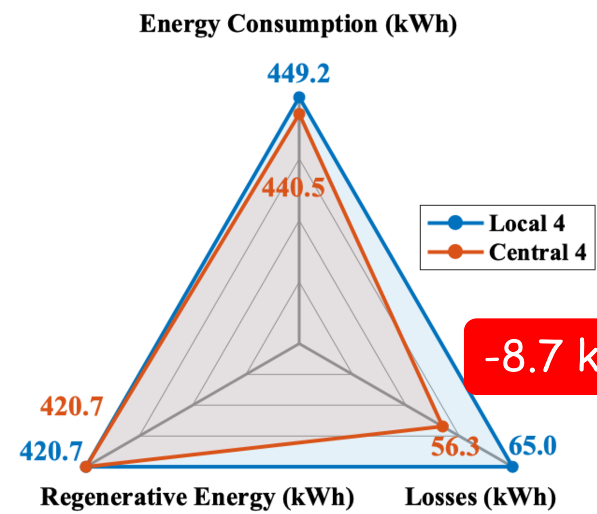


-7.5 kWh

over 5 minutes

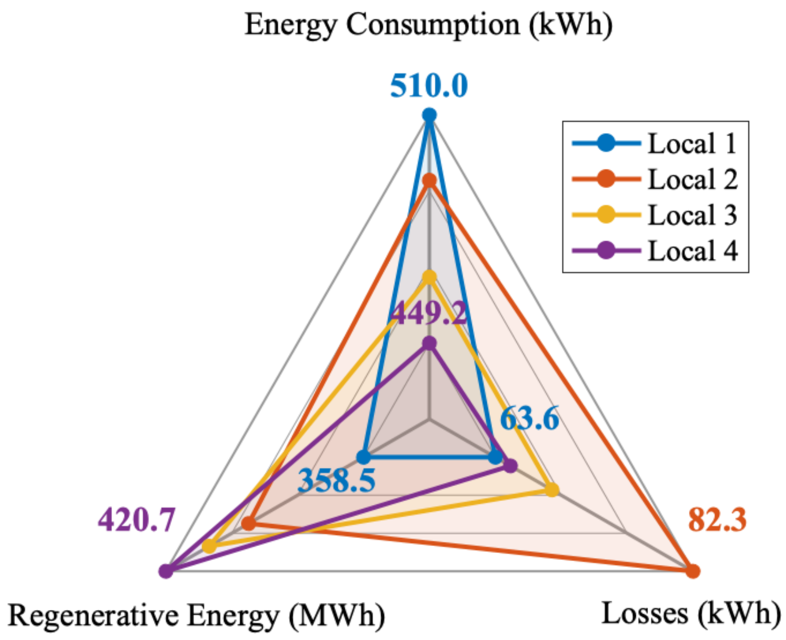


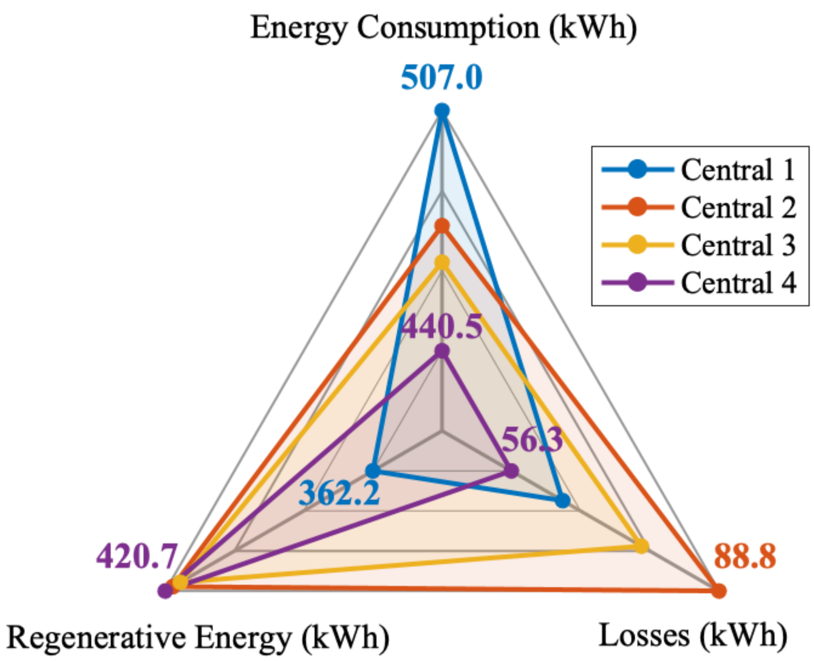
-1.8 kWh



-8.7 kWh

NUMERICAL RESULTS: LOCAL VS CENTRALISED





CONCLUSION AND FUTURE DEVELOPMENTS

- Conclusions
  - An extensive steady-state model of the traction network has been presented
  - The main differences between the conventional local control and the centralised paradigm have been outlined
  - Four centralised control strategies have been proposed and their effectiveness has been highlighted through numerical results (**MWh of saved energy extending the results to the daily service**)

- Future Developments
  - Experimental implementation
  - Assessing the applicability of the decentralized paradigm

THANK YOU FOR THE ATTENTION!