Università degli Studi di Napoli Federico II

Emanuele Fedele

Integration and Control of NPC Multi-Source Inverters for Multimode Rail Vehicles

Tutor: Prof. Diego Iannuzzi
co-Tutor: Prof. Andrea Del Pizzo

Cycle: XXXV

Year: 2021/2022

Background information

- MSc in Electrical Engineering – Università degli Studi di Napoli Federico II
- Research group: Electrical Machines, Converters and Drives (ING-IND/32)
- PhD start and end dates: 01/12/2019 – 30/11/2022
- Scholarship type: MUR PON ("Dottorati Innovativi con Caratterizzazione Industriale")
- Partner company: Hitachi Rail S.p.A.
- Periods abroad (remote):
  Univ. of Birmingham, UK, 1/12/2020-31/05/2021
- Periods in company (blended: remote and in-presence):
  1/06/2021 – 31/08/2022

Summary of study activities

- Courses, PhD schools, Tutorials

Gate Drivers and Control Circuits for IGBTs and MOSFETs, by Prof. Martin Pfost (TU Dortmund), external course organized by the European Center for Power Electronics;

EMC in Power Electronics, by Prof. Eckart Hoene (Fraunhofer IZM), external course organized by the European Center for Power Electronics;

European PhD School on Power Electronics, Electrical Machines, Energy Control and Drives, organized by Università di Cassino, European Center for Power Electronics, and Associazione Nazionale Azionamenti Elettrici.

Sustainable Ship for the Energy Transition of the Maritime Transport, by Prof. Tommaso Coppola (UNINA), organized by ITEE.

Research area

My research is focused on the traction systems of **multimode rail vehicles**, equipped with **alternative primary sources** and **onboard storage devices** for increased efficiency, lower or null local emissions, and medium- to long-range wireless operation.

Research results

- Development of a new **modulation technique** for NPC Multi-Source Inverters (MSIs) for better control of dc currents and ac voltages.
- **Integration** and **control** of MSIs in a non-conventional semi-two-stage traction architecture with significative partial-power-processing features under the operation of conventional energy management strategies.
- **Benchmarking** against standard architectures for **real-case simulation** studies based on the design of real multimode vehicles, with positive outcomes in terms of **volume reductions** of the onboard dc/dc converter.

Main research products (3rd year)

[J1]	**E. Fedele**, D. Iannuzzi, P. Tricoli, A. Del Pizzo, NPC-based Multi-Source Inverters for Multimode DC Rail Traction Systems, IEEE Transactions on Transportation Electrification, Early Access, 2022.
[J2]	**E. Fedele**, A. Cervone, I. Spina, D. Iannuzzi, A. Del Pizzo, Multi-Objective Vector Modulation for Improved Control of NPC-based Multi-Source Inverters in Hybrid Traction Systems, IEEE Journal on Emerging and Selected Topics in Power Electronics, Early Access, 2022.
[C1]	A. Di Pasquale, **E. Fedele**, D. Iannuzzi, M. Pagano Contribution of Wayside Energy Storage Systems to Short Circuit Currents in DC Railway Traction Power Systems, 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia), Himeji, Japan, May 2022, pp. 1101-1106, IEEE.
[C2]	**E. Fedele**, A. Di Pasquale, D. Iannuzzi, M. Pagano Integration of Onboard Batteries and Supercapacitors Based on the Multi-Source Inverter for Light Rail Vehicles, 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia), Himeji, Japan, May 2022, pp. 698-704, IEEE
[C3]	**E. Fedele**, D. Iannuzzi,I. Spina, Semi-Two-Stage Traction System based on the NPC Multisource Inverter for Tram Vehicles with Onboard Supercapacitors, 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Sorrento, Italy, June 2022.

PhD thesis overview

- Problem statement

Multimode rail vehicles enable higher efficiencies, lower emissions and wireless capability. However, they need at least one **high-current dc/dc converter** sized for peak power demands that interfaces the low-voltage power source/storage device to the system dc-bus. A more compact solution would be attractive for manufacturers.

PhD thesis overview

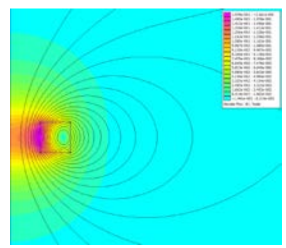
- Objective

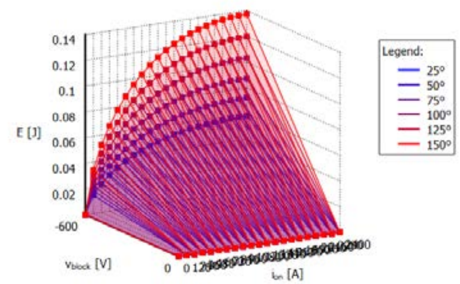
The thesis explores the adoption of an NPC inverter as main ***multi-source* traction inverter** in a **semi-two-stage** traction architecture. Due to the additional connection between the low-voltage source and the motors, the peak-power rating of the dc/dc converter can be **downsized**, and its weight and volume reduced accordingly.

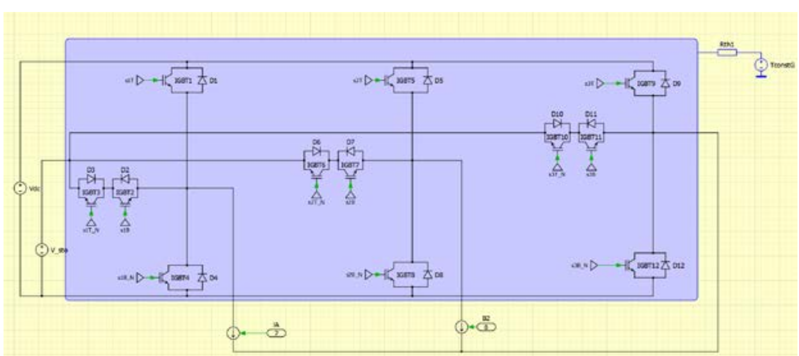
PhD thesis overview

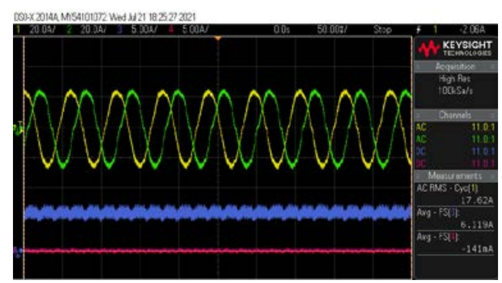
- Methodology

To this aim, proper **control and coordination strategies** of the MSI and dc/dc converters are developed. The proof of concept is **validated experimentally** on a small-scale multimode traction system simulator comprising a wheel-set, an NPC converter, and a battery pack. The effective benefits of the MSI-based semi-two-stage topology for **real-case multimode vehicle designs** are quantified by means of thorough **electrical, magnetic, and thermal simulations** for two case studies: a battery tram, and a fuel cell light train.









Multimode rail vehicles

Bombardier *Flexity 2*
catenary/battery tram

Hitachi *Blues*
catenary/battery/diesel train

CAF *Urbos*
catenary/supercap tram

Alstom *Coradia iLint*
fuel cell/battery train

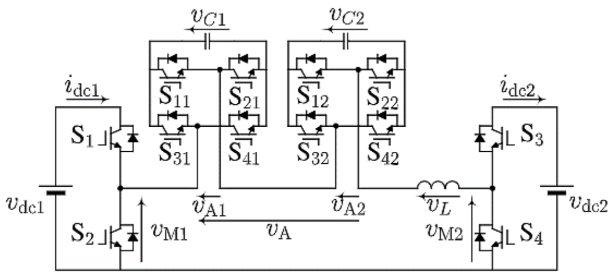
Multimode rail vehicles

- Braking-energy recovery with high efficiency
- Line current reduction and voltage stabilization
- No investments in electrified infrastructure
- Potential catenary-free operation with reduced or zero local emissions
- Reduced level of visual intrusion in historical areas (e.g., old city centers).

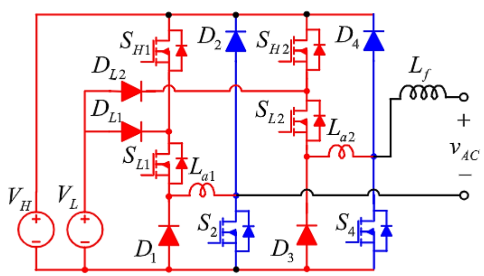
Multimode rail vehicles

- Increased vehicle costs
- More stringent safety requirement and constraints
- Mass and volume of additional power electronics impose restrictions on the vehicle design

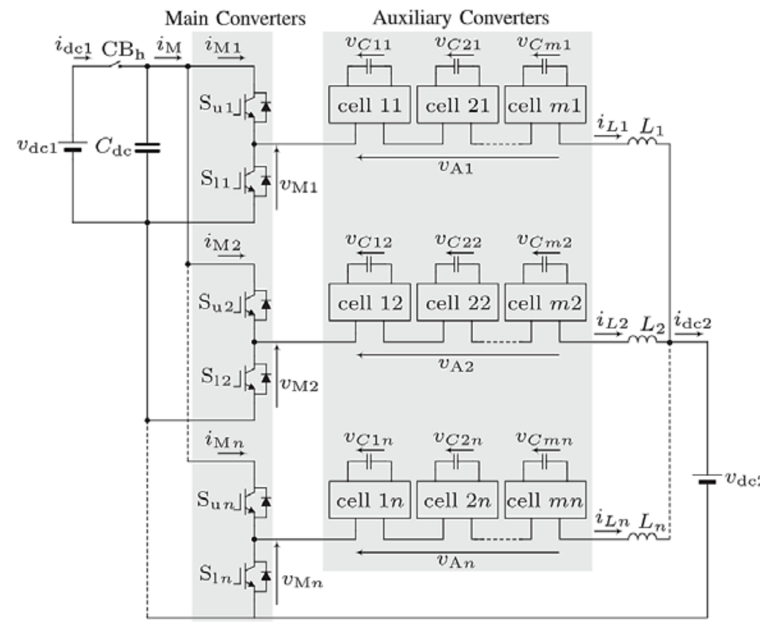
Recent concepts for dc/dc and dc/dc conversion



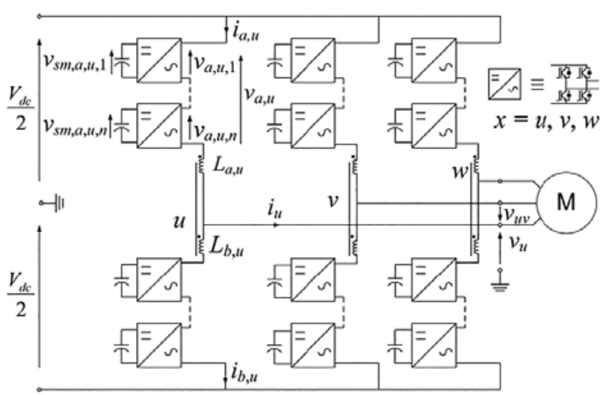
Bidirectional dc/dc converter with auxiliary converter



Dual-dc-port dual-buck inverter



Interleaved bidirectional dc/dc converter



Boost modular cascaded inverter

Cascaded inverters with dual-three phase motor

The NPC Multi-Source Inverter (MSI)

It shares the same circuit topology of an NPC (left) or T-NPC (right) multilevel inverter, but it is fed by **two independ dc-buses at different voltage levels**. In standard NPC multilevel inverters, the PWM modulation has to control the average central-point current to zero to keep its voltage at half of the dc-link voltage. In NPC MSIs, the input voltages are fixed by the external dc sources, and an **active control on the dc input currents is needed** to control the power flows among the traction loads and the dc buses.

The Multi-Objective Vector Modulation (MOVM)

As the state-of-literature interleaved SVM suffers from many limitations, **a novel PWM modulation strategy** is envisioned for the MSI. It exploits the space-vector model of the converter to control the input currents and ac voltages with increased control flexibility and reduced ripples.

$$\begin{cases} d_{\Delta\alpha} = \dfrac{i^*_{\mathrm{LV}}}{p_{\mathrm{ac}}} v^*_\alpha \\ d_{\Delta\beta} = \dfrac{i^*_{\mathrm{LV}}}{p_{\mathrm{ac}}} v^*_\beta \\ d_{\mathrm{B}\alpha} = \dfrac{1}{V_{\mathrm{HV}}} (v^*_\alpha + \Delta V \dfrac{i^*_{\mathrm{LV}}}{p_{\mathrm{ac}}} v^*_\alpha) \\ d_{\mathrm{B}\beta} = \dfrac{1}{V_{\mathrm{HV}}} (v^*_\beta + \Delta V \dfrac{i^*_{\mathrm{LV}}}{p_{\mathrm{ac}}} v^*_\beta) \end{cases}$$

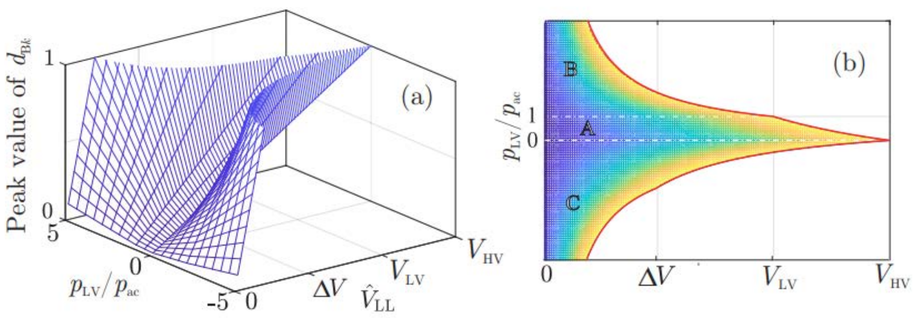
MOVM power limits

The **limits of linear modulation** define **the minimum and maximum power** that can be drawn from or injected into the LV-bus. The limits do not depend on the ac power, but do depend on the ac voltage magnitude and dc voltage levels. The LV bus power p_{dc2} can be either positive or negative, smaller or greater than the load power up to a peak-to-peak ac fundamental voltage equal to the LV-bus voltage level

$$\mathrm{LT}(\hat{V}_{\mathrm{LL}}, V_{\mathrm{HV}})p_{\mathrm{ac}} \leq p_{\mathrm{LV}} \leq \mathrm{UT}(\hat{V}_{\mathrm{LL}}, V_{\mathrm{HV}}, V_{\mathrm{LV}})p_{\mathrm{ac}}$$

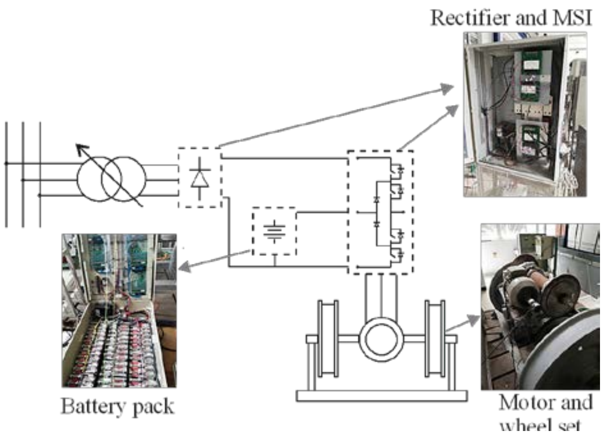
$$\mathrm{LT} = \begin{cases} -\dfrac{V_{\mathrm{dc2}}}{\hat{V}_{\mathrm{LL}}}, & \mathrm{for}\, \hat{V}_{\mathrm{LL}} \leq \Delta V \\ \dfrac{\hat{V}_{\mathrm{LL}} - V_{\mathrm{dc1}}}{\hat{V}_{\mathrm{LL}}}, & \mathrm{for}\, \hat{V}_{\mathrm{LL}} \geq \Delta V \end{cases}$$

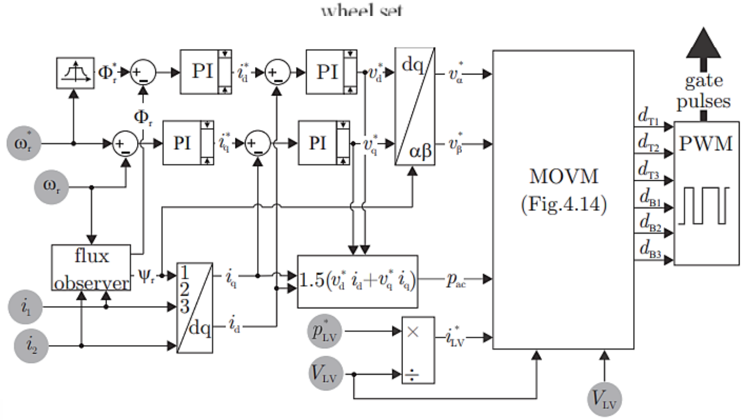
$$\mathrm{UT} = \begin{cases} \dfrac{V_{\mathrm{dc2}}}{\hat{V}_{\mathrm{LL}}}, & \mathrm{for}\ \hat{V}_{\mathrm{LL}} \leq V_{\mathrm{dc2}} \\ \dfrac{V_{\mathrm{dc1}} - \hat{V}_{\mathrm{LL}}}{\hat{V}_{\mathrm{LL}}} \cdot \dfrac{V_{\mathrm{dc2}}}{\Delta V}, & \mathrm{for}\ \hat{V}_{\mathrm{LL}} \geq V_{\mathrm{dc2}} \end{cases}$$

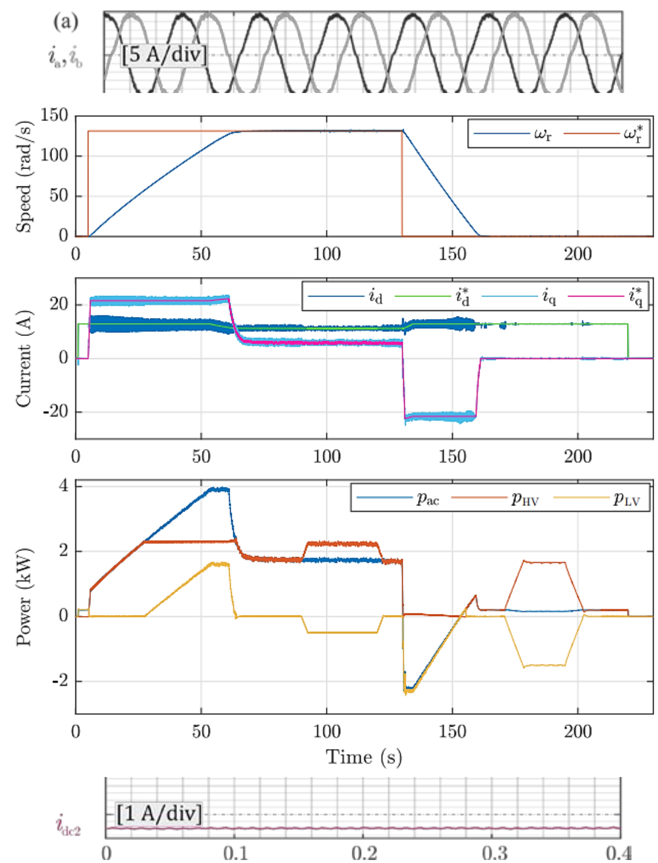


MOVM experimental validation

The MOVM has been **validated experimentally** on a small-scale bimode traction drive in both **steady-state** and **dynamic** driving conditions.

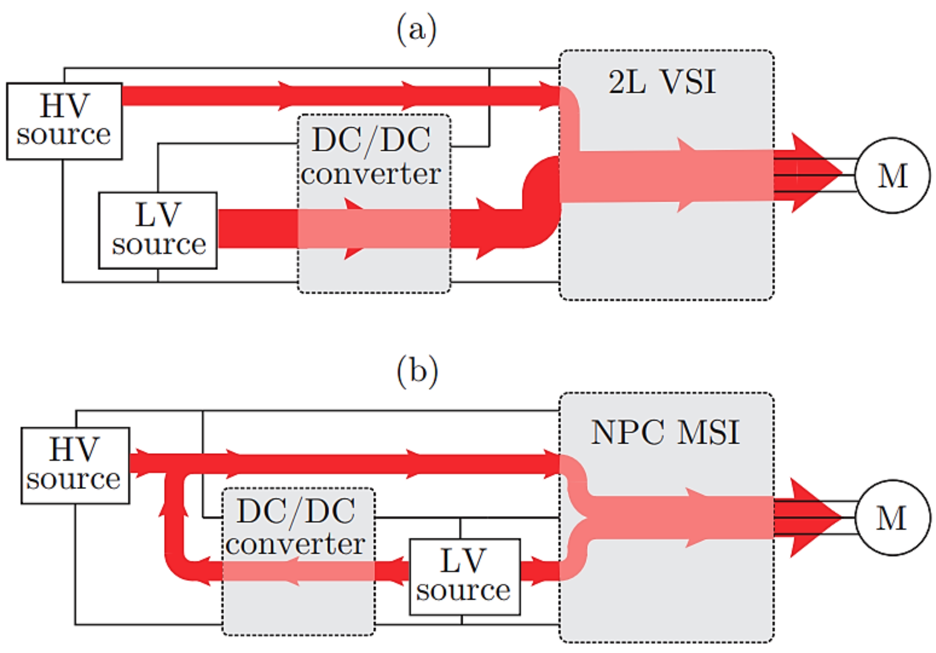






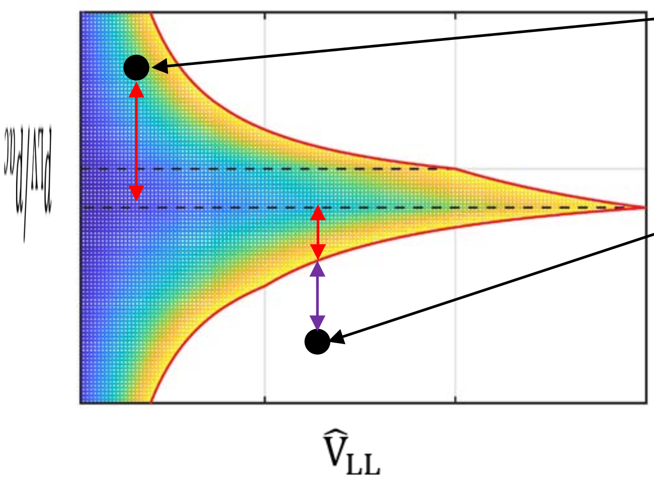
MSI-based semi-two-stage(S2S) architecture

For high motor speeds and/or low LV-bus voltage levels, the MOVM power limits may be uncompatible with system-level power-sharing requirement. For this reason, **a dc/dc converter is still required**. However, the integration of the MSI into the traction system leads to a **semi-two-stage architecture**, where the dc/dc converter can be partly bypassed, and its peak power rating reduced accordingly.



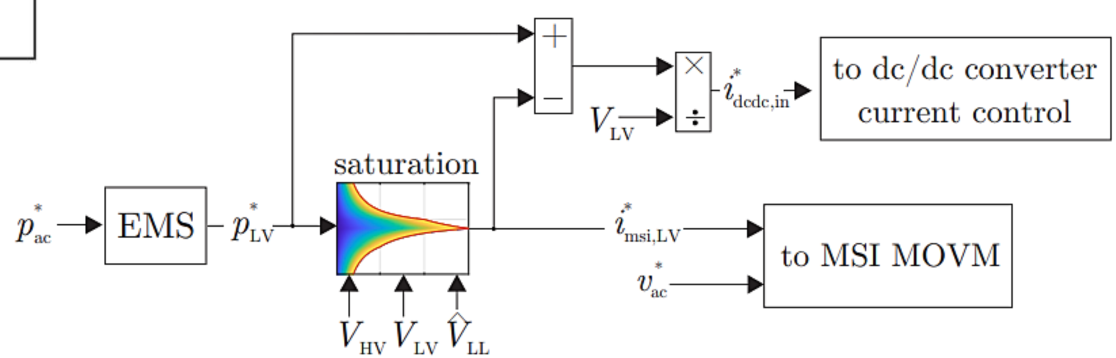
Coordination strategy

A coordination strategy must be envisioned to **split the LV-source power** between the dc/dc converter and the MSI in order to **minimize the power flowing through the onboard chopper** without exceeding the MSI modulation limits.



Any amount of power that falls inside the MOVM operating plane is managed by the MSI, and dc/dc converter is bypassed.

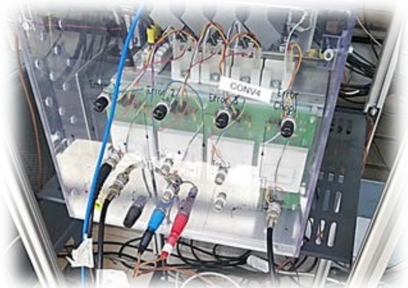
In case the LV power exceeds the MSI limits, the MSI operates at maximum power while the chopper processes the extra amount.

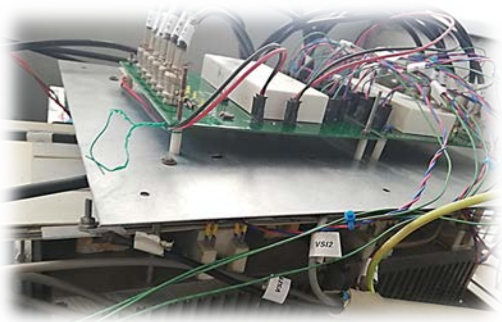


Experimental validation

The S2S coordination and control concepts have been validated **experimentally** for **two possible arrangements of the dc sources**:

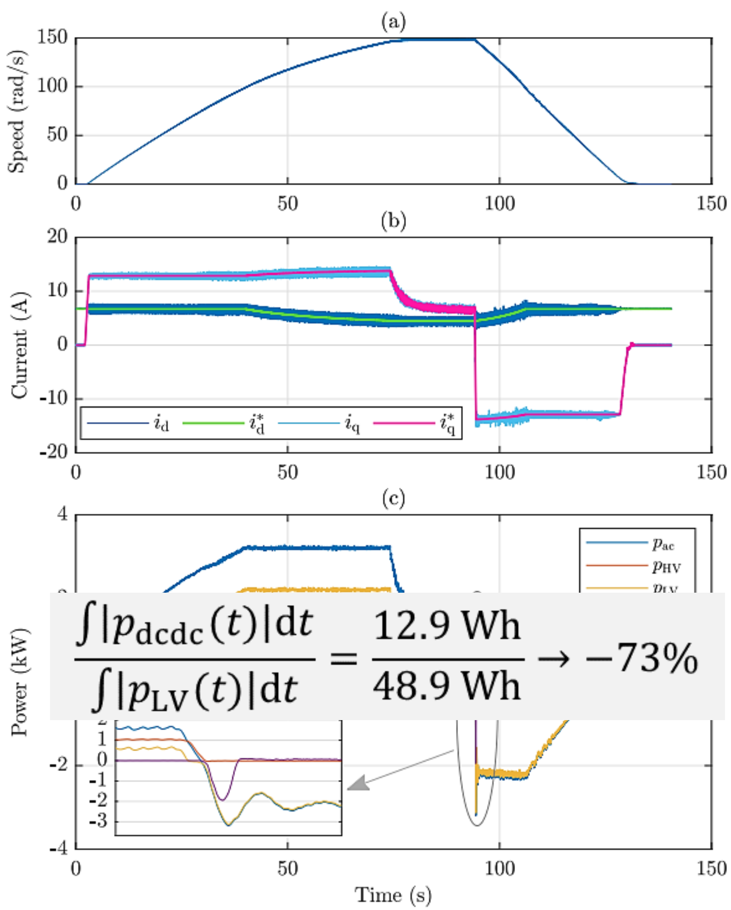
1. Non-receptive diode rectifier on the HV-bus, battery pack on the LV-bus (as in case of catenary/battery rail vehicles).
2. Battery on the HV bus, non-receptive dc power supply on the LV-bus (as in case of fuel cell/battery vehicles).



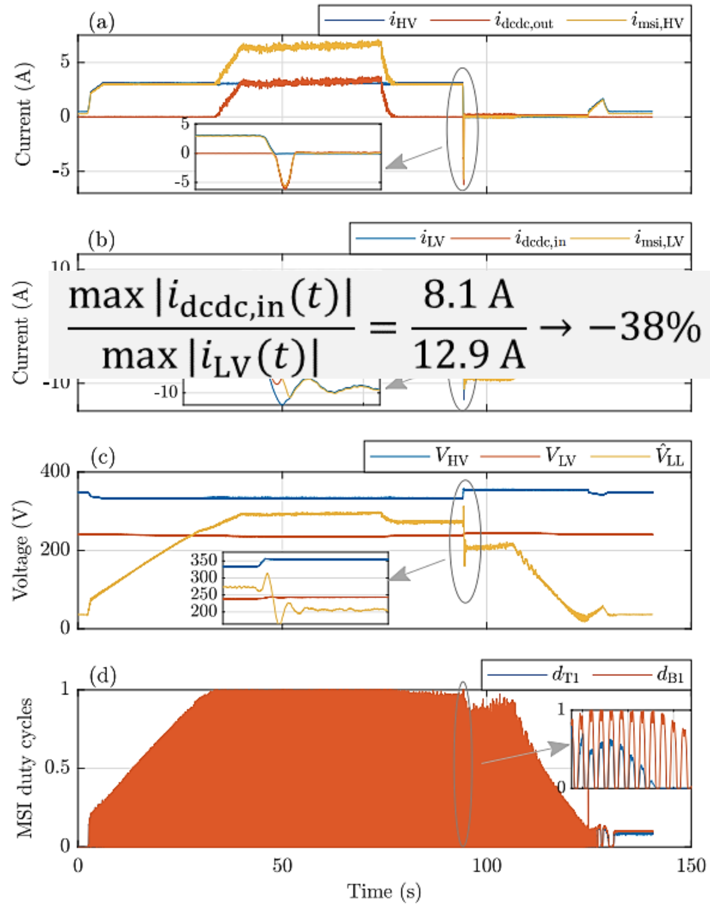


Experimental validation #1

Non-receptive diode rectifier on the HV-bus, battery pack on the LV-bus.



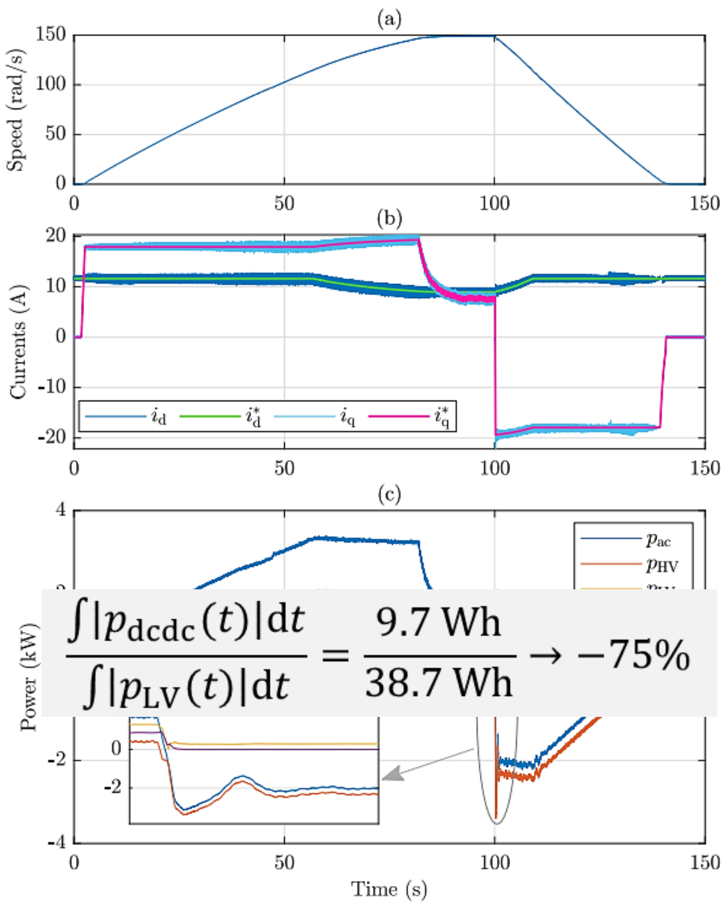
$$\frac{\int |p_{\mathrm{dcdc}}(t)|\mathrm{d}t}{\int |p_{\mathrm{LV}}(t)|\mathrm{d}t} = \frac{12.9\ \mathrm{Wh}}{48.9\ \mathrm{Wh}} \rightarrow -73\%$$



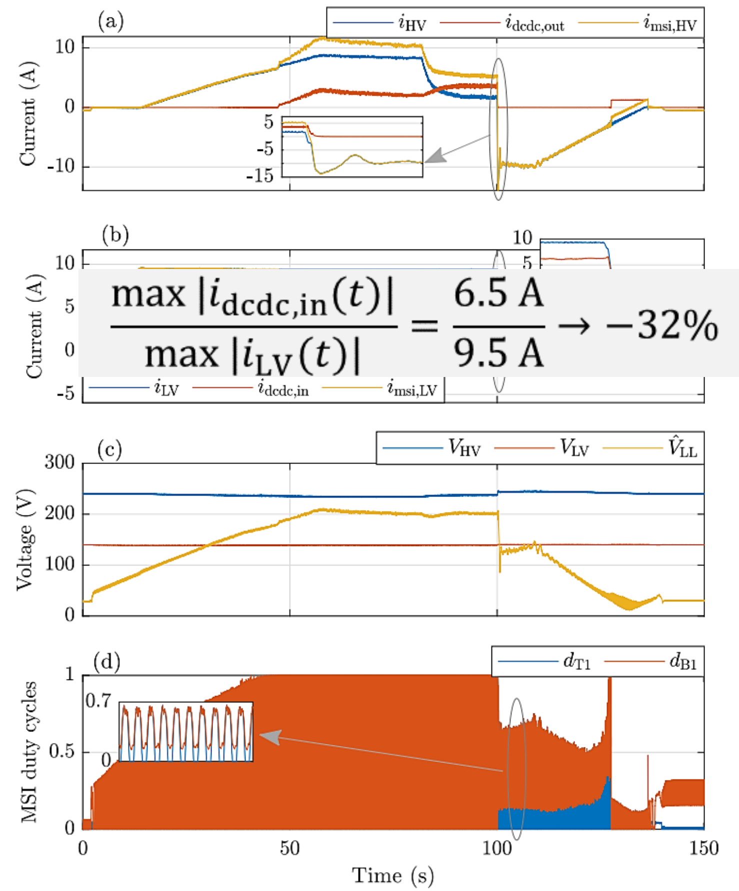
$$\frac{\max |i_{\mathrm{dcdc,in}}(t)|}{\max |i_{\mathrm{LV}}(t)|} = \frac{8.1\ \mathrm{A}}{12.9\ \mathrm{A}} \rightarrow -38\%$$

Experimental validation #2

Non-receptive dc power supply on the LV-bus, battery pack on the HV-bus.



$$\frac{\int |p_{\mathrm{dcdc}}(t)|\mathrm{d}t}{\int |p_{\mathrm{LV}}(t)|\mathrm{d}t} = \frac{9.7\ \mathrm{Wh}}{38.7\ \mathrm{Wh}} \rightarrow -75\%$$

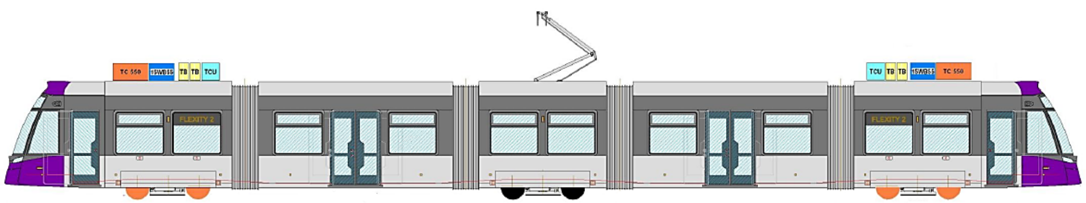


$$\frac{\max |i_{\mathrm{dcdc,in}}(t)|}{\max |i_{\mathrm{LV}}(t)|} = \frac{6.5\ \mathrm{A}}{9.5\ \mathrm{A}} \rightarrow -32\%$$

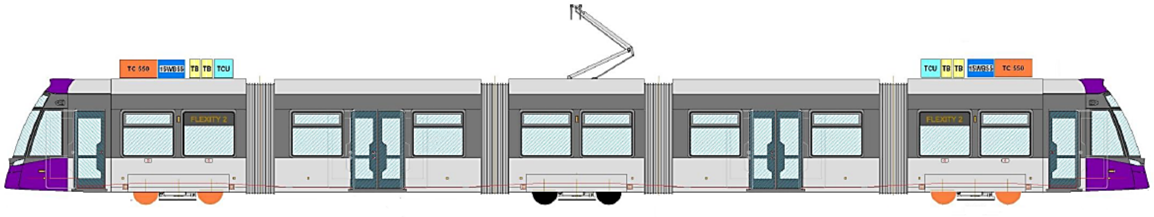
Comparative numerical analysis

The experiments have validated the proof of concept and shown the potential of the envisioned S2S topology. However, what are the actual benefits if the MSI is integrated in a real multimode vehicle?

To answer this question, extensive circuit, magnetic, and thermal simulations for two two real-case studies are carried out: the catenary/battery tram *Flexity 2* in Nanjing (China), and the fuel cell/battery train *FV-E991* by Hitachi and JR East in Japan.



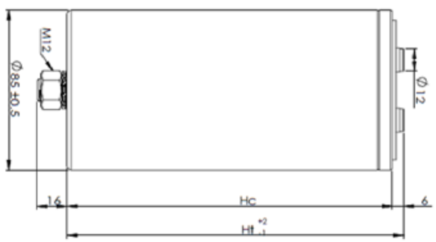
Flexity 2 tram traction system architectures



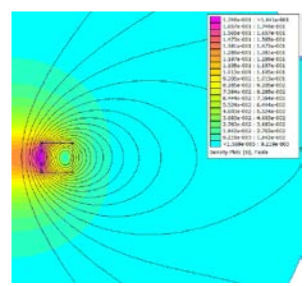
FV-E991 train traction system architectures

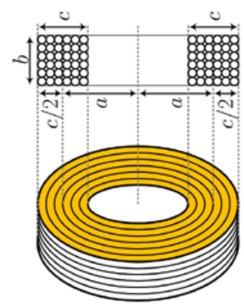
Sizing and selection of components

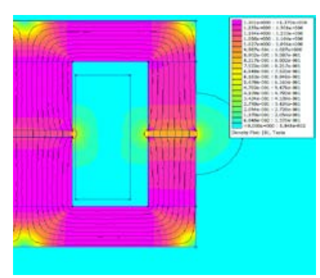
DC film capitors are dimensioned according to voltage-ripple constaints and selected off-the-shelf from the portfolio of manufacturer TDK.

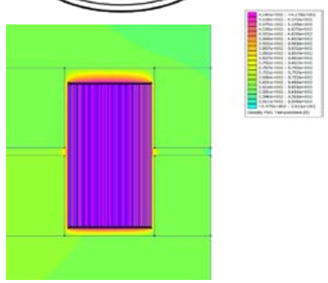


Filter inductors at the input of the dc/dc converter and on the HV-bus are sized according to current-ripple constraints and are designed with the aid of magnetic and thermal FEM simulations.

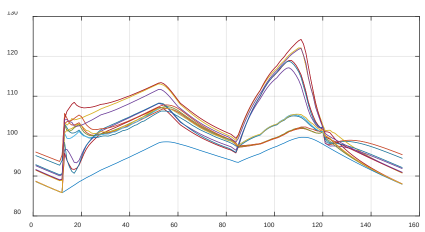


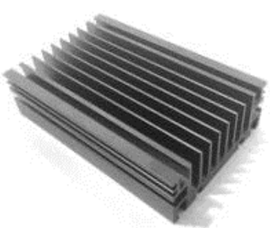




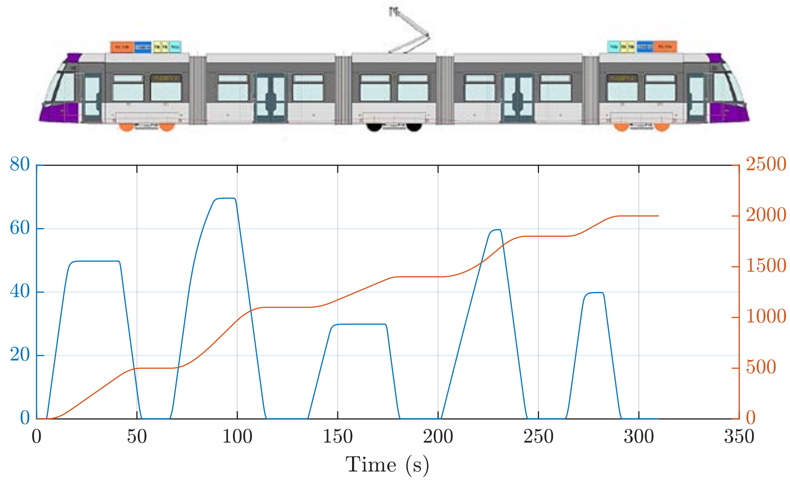


Air-cooled extruded heatsinks are sized to limit the maximum junction temperatures to 125°C and are selected from the portfolio of manufacturer ABL.

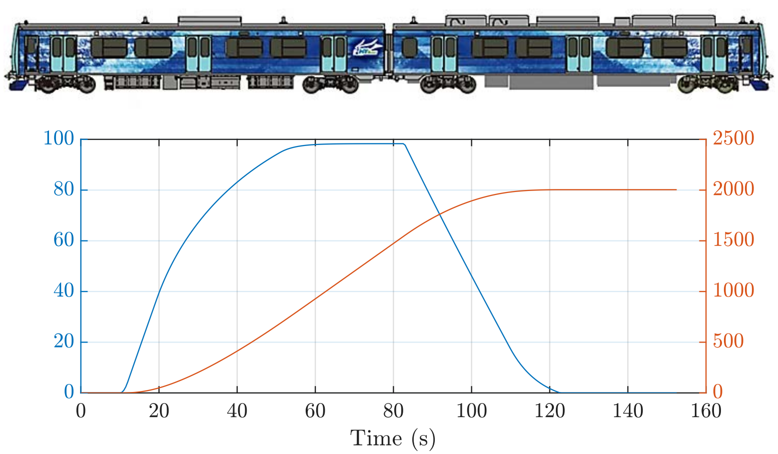




Results



	Standard 2S architecture	MSI-based S2S architecture
Cycle energy losses in two traction motors (Wh)	624.7	625.3 (+ 0.1 %)
Cycle energy losses in each traction inverter (Wh)	265.4	227.2 (-14.4%)
Cycle energy losses in each dc/dc converter (Wh)	78.1	31.2 (-60.0 %)
Cycle energy losses in the traction system (kWh)	1.93	1.77 (- 8.3 %)
Volume of passive filters and heat sinks in each traction inverter (lt)	90.2	93.5 (+ 3.7 %)
Volume of passive filters and heat sinks in each dc/dc converter (lt)	71.6	47.2 (-34 %)



	Standard 2S architecture	MSI-based S2S architecture
Cycle energy losses in two traction motors (Wh)	354.9	355.8 (+0.2 %)
Cycle energy losses in each traction inverter (Wh)	188.0	187.6 (-0.2 %)
Cycle energy losses in each dc/dc converter (Wh)	58.0	31.1 (-46.38%)
Cycle energy losses in the traction system (kWh)	1.144	1.149 (+0.4 %)
Volume of passive filters and heat sinks in each traction inverter (lt)	65.3	71.9 (+10%)
Volume of passive filters and heat sinks in each dc/dc converter (lt)	60.4	32.8 (-45.7%)

Conclusions

- A semi-two-stage traction system based on the proper integration and control of the NCP Multi-Source Inverter for multimode rail vehicles has been explored for the first time.
- A novel modulation algorithm of the MSI, as well as a coordination strategy to manage the MSI and dc/dc converters, have been developed and validated through extensive experimental tests. They allow a versatile operation of the S2S system in compliance with the power-sharing targets set by typical energy management strategies of multimode rail vehicles.
- Comprehensive simulations for two case studies based on the design data of real bimode vehicles show that the envisioned system can bring significant reductions in the volume required by the onboard dc/dc converter. However, this result comes with a minor increase in the volume and a higher VA rating and cost of the traction inverter, due to the doubled number of semiconductors needed.