Università degli Studi di Napoli Federico II
PhD program in
Information Technology and Electrical Engineering

PhD Student: Emanuele Fedele

Cycle: XXXV

Training and Research Activities Report

Academic year: 2020-21 - PhD Year: Second

Tutor: Prof. Diego Iannuzzi

Co-Tutors: Prof. Andrea Del Pizzo, Ing. Luigi Fratelli

Date: October 21, 2021

1. Information:

- **PhD student: Emanuele Fedele** **PhD Cycle: XXXV**
- **DR number: DR994202**
- **Date of birth: 24/05/1994**
- **Master Science degree: Electrical Engineering** **University: Università degli Studi di Napoli "Federico II"**
- **Scholarship type: MUR PON**
- **Tutor: Prof. Diego Iannuzzi**
- **Co-tutor: Prof. Andrea Del Pizzo, Ing. Luigi Fratelli**

2. Study and training activities:

Activity	Type[1]	Hours	Credits	Dates	Organizer	Certificate[2]
"Scientific Programming and Visualization with Pyhton"	Courses	18	2	8/3/2021 – 10/3/2021	DiSt (UNINA)	Y
"Statistical Data Analysis for Science and Engineering"	Courses	12	4	17/2/2021 – 4/3/2021	Dr. Roberto Pietrantuono (DIETI, UNINA)	Y
"Reti Elettriche Complesse e Simulazione Circuitale"	Courses	84	9	8/3/2021 – 10/6/2021	Prof. Massimiliano de Magistris (DIETI, UNINA)	Y
"European PhD School on Power Electronics, Electrical Machines, Energy Control and Power Systems"	Doctoral School	40	4	12/7/2021 – 16/7/2021	Università di Cassino and European Center for Power Electronics	Y
"Reliability of modern power electronic based power systems"	Seminar	1	0.2	17/11/2020	IEEE PELS	Y
"Towards sustainable and reliable automated design of power electronics systems"	Seminar	1	0.2	19/11/2020	IEEE PELS	Y

"Patent searching best practices with IEEE Xplore"	Seminar	1	0.2	27/11/2020	DIETI	Y
"Advances in machine learning for modelling and understanding in earth sciences"	Seminar	1	0.2	27/1/2021	IEEE Geoscience and Remote Sensing	N
"Designing a socially assistive robot for adaptive and personalized assistance to patients with dementia"	Seminar	1	0.2	17/2/2021	Prof. Rossi (PRISCA Lab, DIETI)	Y
"Introduction of a State-of-the-Art Power Electronics Design Automation Tool in Hitachi ABB power grids – Challenges and Best Practices"	Seminar	1	0.2	25/2/2021	IEEE PELS	Y
"Emotions in reinforcement learning agents"	Seminar	1	0.2	17/3/2021	Prof. Rossi (PRISCA Lab, DIETI)	Y
"Robust control of grid-connected converter: a 15-year evolutionary timeline"	Seminar	1	0.2	23/3/2021	IEEE PELS	Y
"High-performance heat sink design for WBG power modules using Genetic Algorithms"	Seminar	1	0.2	25/3/2021	IEEE PELS	Y
"High-density motor drive design for electric aircraft propulsion"	Seminar	1	0.2	13/4/2021	IEEE PELS	Y
"EMI reduction techniques For automotive power conversion"	Seminar	1	0.2	22/4/2021	IEEE PELS	Y

"Opportunities, challenges and Potential Solutions in High-frequency WBG Motor Drives"	**Seminar**	**1**	**0.2**	**6/5/2021**	**IEEE PELS – IEEE TEC**	**Y**
"Short and ultrashort, high voltage electric pulses for biological and medical applications"	**Seminar**	**1.5**	**0.3**	**13/5/2021**	**Prof. Rita Massa (Fisica, UNINA)**	**N**
"L'avvincente storia degli acceleratori"	**Seminar**	**1.5**	**0.3**	**14/5/2021**	**Prof. Rita Massa**	**N**
"A stochastic first-order trust-region method with inexact restoration for nonconvex optimization"	**Seminar**	**1**	**0.2**	**18/5/2021**	**Prof. Daniela di Serafino (Dip. Matematica, UNINA)**	**N**
"Power Electronics for Precision Farming with Sustainable and Cleaner Environment"	**Seminar**	**1**	**0.2**	**18/5/2021**	**IEEE PELS – IEEE TEC**	**Y**
"Introduction to legged robots and examples of IIT's dynamic legged systems Lab"	**Seminar**	**2**	**0.4**	**26/5/2021**	**Dr. Fabio Ruggiero (DIETI)**	**Y**
"A Mission-profile-based Reliability Assessment Software Tool for the Design of Power Electronics Systems"	**Seminar**	**1**	**0.2**	**28/5/2021**	**IEEE PELS**	**Y**
"5G: l'architettura, le applicazioni e la rete di accesso radio	**Seminar**	**2**	**0.4**	**8/6/2021**	**Prof. Nicola Pasquino (DIETI)**	**N**
"Advanced Health-Conscious	**Seminar**	**1**	**0.2**	**15/6/2021**	**IEEE PELS**	**Y**

Fast Charging Schemes and Battery Management Systems for E-mobility”						
“Testing Inverters using Electric Motor Emulators: Benefits, Challenges”	**Seminar**	**1**	**0.2**	**29/6/2021**	**IEEE PELS**	**Y**
“L’esposizione ai campi elettromagnetici generati dal sistema 5G - Metodologie scalari e vettoriali di misura dell'esposizione e tecniche di estrapolazione”	**Seminar**	**4**	**0.8**	**16/7/2021**	**Prof. Nicola Pasquino**	**Y**
“Adaptive EMC design for wide bandgap power converters in aviation applications”	**Seminar**	**1**	**0.2**	**21/7/2021**	**IEEE PELS – IEEE TEC**	**Y**
“Passives in Power Electronics: Magnetic Components Design and Simulation”	**Seminar**	**11**	**2.2**	**23/9/2021 – 24/9/2021**	**European Center for Power Electronics**	**Y**

1) Courses, Seminar, Doctoral School, Research, Tutorship
2) Choose: Y or N

2.1. Study and training activities - credits earned

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1	0	0.6	7	0	7.6
Bimonth 2	0	0.6	5	0	5.6
Bimonth 3	6	1	8	0	15
Bimonth 4	9	2.9	8	0	19.9
Bimonth 5	4	1	8	0	13
Bimonth 6	0	2.2	4	0	6.6
Total	19	8.3	40	0	67.3
Expected	30 - 70	10 - 30	80 - 140	0 – 4.8	

3. Research activity:

The main research activities during the second year of PhD have been focused on the following topics related to rail traction in general and multimode rail vehicles in particular:

3.1 Multi-Source Inverter for alternative traction systems in multimode rail vehicles

The multi-source inverter (MSI) has been recently introduced for a compact integration of multiple sources and traction motor drives in automotive powertrains [1]. In particular, it is intended for the single-stage interconnection between DC sources and AC loads. Its use in multimode traction systems can reduce the power ratings of DC/DC converters or even avoid them completely [2]. Its conceptual scheme and possible circuit implementations are shown in Fig. 1. The MSI circuit is derived from the circuitry of NPC and T-NPC multilevel converters. However, these two converter families differ since the MSI is supplied by two or more independent DC sources.

After a preliminary analysis of the relevant bibliography, the state-of-literature approach to the control of the MSI has been evaluated by means of analytical modelling, numerical simulations and experimental tests. According to this approach (called "current-sharing control" or CSC, [3]), the MSI is operated as two 2-level inverters that connect the load to one source at a time. By periodically interleaving the operation of the two equivalent inverters and varying the conduction time of each source, the average currents i_{dc1} and i_{dc2} can be regulated to achieve the desired power split between DC sources. The simulations and experimental tests confirmed that the state-of-literature control approach suffers from two main limitations:

- An inherent trade-off between control resolution (i.e., the minimum amount by which the DC power flows can be regulated) and control frequency, the latter determining the size of the input capacitors.
- The unfeasibility of a controlled recharge of one source from the other, either during motor operation or at standstill.

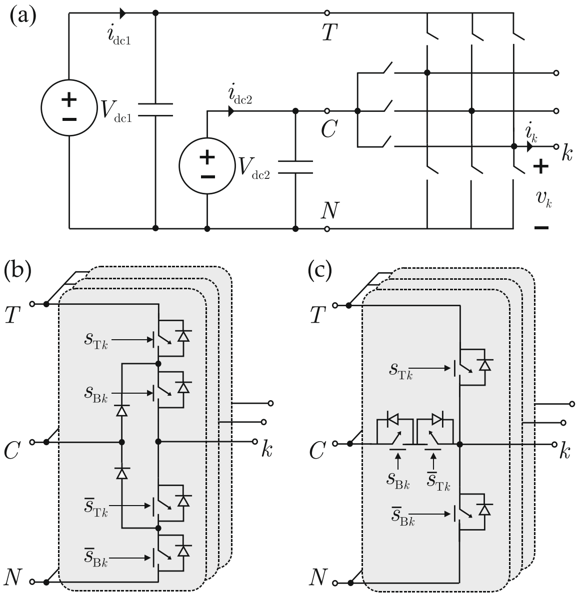


Fig. 1 Multi-source inverter ideal topology (a), and practical circuit implementations (b,c).

The second limitation results in the need to use additional conversion systems to recharge bidirectional storage devices (e.g., onboard batteries or supercapacitors), which in turn has a negative impact on the attractiveness of the MSI as compact architecture for multimode traction systems.

In result of the theoretical and experimental evaluation of the baseline approach to the MSI control problem, research efforts have been oriented to the derivation of an alternative control method for full control of the DC sources and AC loads without the drawbacks of the CSC method. Starting from the averaged mathematical model of the uncontrolled MSI circuit in the space-vector formalism, a novel multi-objective vector modulation (MOVM) has been derived. This modulation algorithm takes full advantage of the MSI circuit topology and allows to overcome the limits of the baseline CSC approach. In particular, a stable and non-quantized control of the DC power flows can be achieved. Moreover, the controlled recharge of one source from the other can be achieved both with the motor in operation and at standstill.

The effectiveness of the proposed modulation was validated by preliminary experimental tests on a small-scale rail traction system fed by two independent DC sources. The test bench configuration and experimental results are shown in Fig. 2 and Fig.3, respectively.

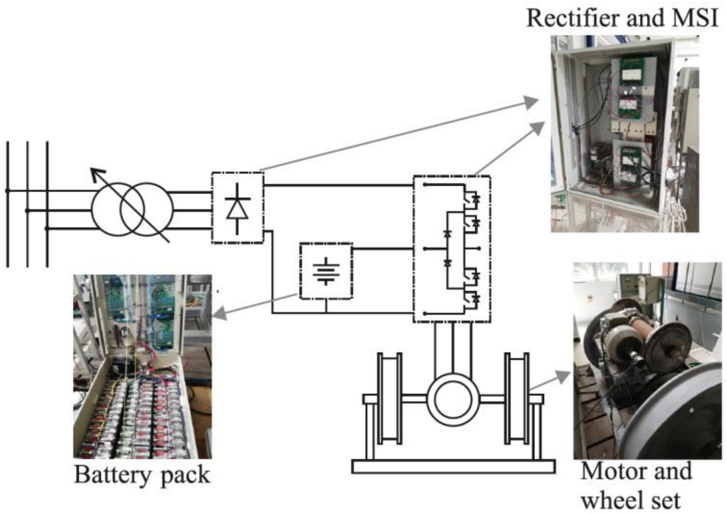


Fig. 2 Test bench layout for the validation of the MOVM strategy.

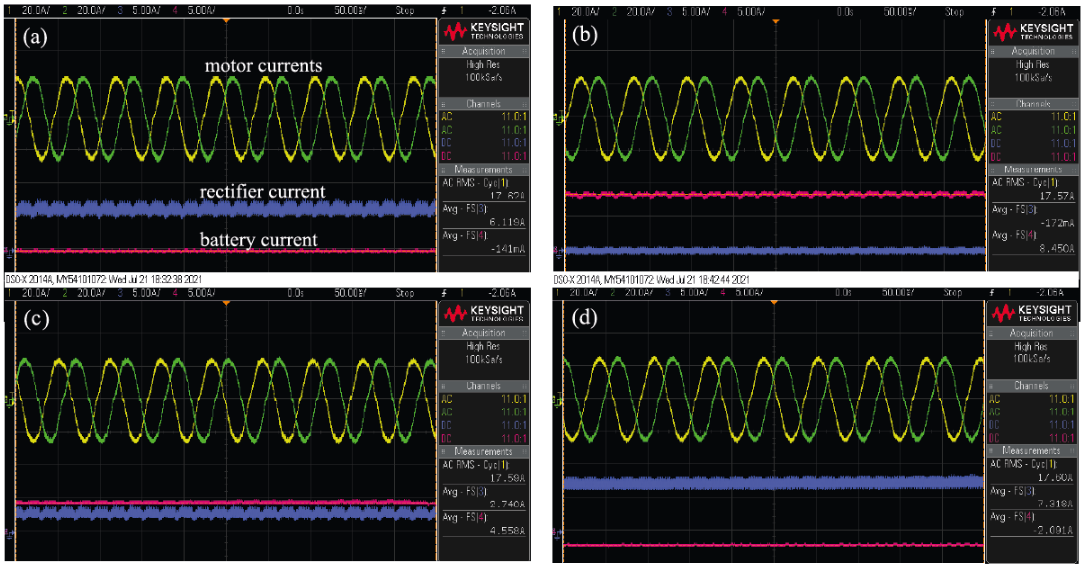


Fig. 3 Experimental waveforms of DC and AC currents under MOVM operation, for a steady-state operation of the motor: (a) The rectifier alone supplies the load; (b) the battery alone supplies the load; (c) both sources supply the load; (d) the rectifier recharges the battery while supplying the load.

As shown by the experimental results, the MOVM allows the MSI to manage the DC sources with a higher versatility than the CSC and can represent an enabling technique for an attractive adoption of MSIs in hybrid traction systems supplied by multiple independent sources.

3.2 Early detection of bearing faults in traction motors based on current and voltage measurements

The state-of-art approach for the condition monitoring of induction motors is based on the time-frequency analysis of vibration signals [4]. In particular, envelope analysis has established itself as a solid procedure for early detection of bearing faults, which can be responsible for up to 40% of the overall machine failures. Alternative techniques based on the processing of electrical quantities (currents and voltages) have gained interest in the academia. In fact, they do not require accelerometers and only rely on voltage and current sensors, which in most cases are already part of the electric traction drive [5]. However, these techniques still belong to early-stage research and lack the maturity and soundness that are required from the industry. The main objective of this research activity was to develop a preliminar experimental bench to empirically assess a correlation between fault, vibration singnals signatures and electrical signals signatures. To this end, vibration, current and voltage measurements were carried out on a grid-supplied induction motor, both under normal conditions and with an artificial defect on the outer cage. A picture of the test bench is given in Figure 4, with a detail of the fault produced on the bearing.

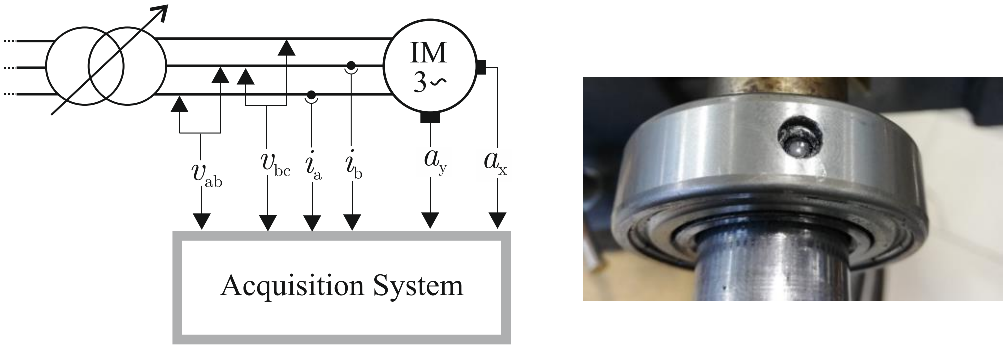


Fig. 4. Test bench layout for the analysis of fault signatures in vibration, current and voltage measurements

The frequency spectrum resulting from the envelope analysis on the vibration signals under normal (left) and faulty (right) operation are shown in Fig. 5. Vibration analysis represents here a solid tool for fault detection, as highlighted by the spectral components at multiples of the characteristic bearing frequency that become apparent in the case of fault.

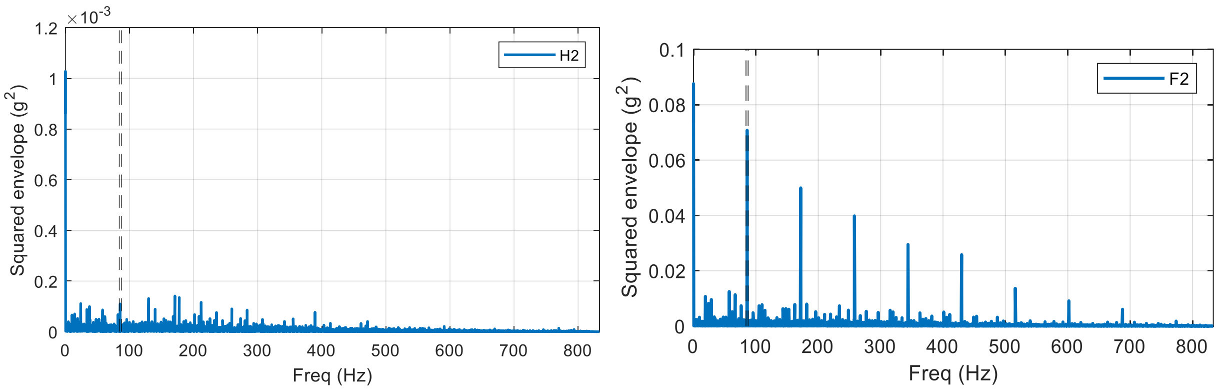


Fig. 5. Squared envelope amplitude spectra of vibration signals with healty (left) and faulty (right) bearing.

The same procedure was applied to current and voltage signals, or to a combination of both (e.g., instantaneous electrical power, instantaneous power factor). Figure 6 represents the frequency spectrum obtained through envelope analysis of the phase current signals. The experimental results show that here the analysis of motor currents fails in revealing the artificial fault on the outer bearing cage, since no relevant component is found where expected (i.e., at the bearing characteristic frequency).

Further analysis are then required to assess the reason behind the failure of such alternative diagnostic approaches and understand which factors can affect their performance.

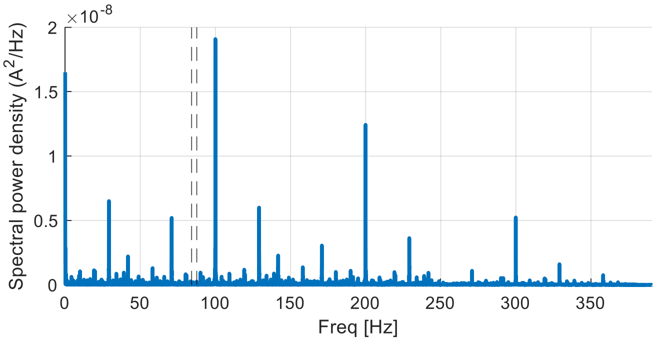


Fig. 6. Squared envelope amplitude spectra of motor currents with faulty bearing.

PARTIAL BIBLIOGRAPHY

[1] L. Dorn-Gomba, P. Magne, B. Danen, and A. Emadi, "On the Concept of the Multi-Source Inverter for Hybrid Electric Vehicle Powertrains," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7376–7386, Sep. 2018, doi: 10.1109/TPEL.2017.2765247.

[2] L. Dorn-Gomba, J. Guo, and A. Emadi, "Multi-Source Inverter for Power-Split Hybrid Electric Powertrains," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6481–6494, Jul. 2019, doi: 10.1109/TVT.2019.2915173.

[3] L. Dorn-Gomba, E. Chemali, and A. Emadi, "A novel hybrid energy storage system using the multi-source inverter," in *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, Apr. 2018, vol. 2018-March, pp. 684–691, doi: 10.1109/APEC.2018.8341086.

[4] R. B. Randall and J. Antoni, "Rolling element bearing diagnostics-A tutorial," *Mechanical Systems and Signal Processing*, vol. 25, no. 2. 2011, doi: 10.1016/j.ymssp.2010.07.017.

[5] Y. Gritli, A. Bellini, C. Rossi, D. Casadei, F. Filippetti, and G. A. Capolino, "Condition monitoring of mechanical faults in induction machines from electrical signatures: Review of different techniques," in *Proceedings of the 2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, SDEMPED 2017*, 2017, vol. 2017-Janua, doi: 10.1109/DEMPED.2017.8062337.

4. Research products

Fedele, E.; Iannuzzi, D.; Del Pizzo, A.
"Onboard energy storage in rail transport: Review of real applications and techno-economic assessments"
IET Electrical Systems in Transportation (published as early access), 2021.

Fedele, E.; Iannuzzi, D; Tricoli, P.; Del Pizzo, A.
"Characterisation of the Multi-Source Inverter for Multimode Rail Traction Systems"
Submitted to IEEE Transactions on Vehicular Technology, first revision undergoing.

Participation to the best poster award during the poster session of the 2021 International PhD School organized by Università di Cassino.

5. Conferences and seminars attended

- "PhD International School on Power Electronics, Electrical Machines, Energy Control and Power Systems" (online event), 12-16 July 2021, organized by University of Cassino, European Center for Power Electronics, and Associazione Nazionale Azionamenti Elettrici. I presented a poster on my current research activity in the junior PhD poster session.
- ECPE Tutorial: "Passives in Power Electronics: Magnetic Components Design and Simulation" (online event), 23-24 Sept. 2021, organized by European Center for Power Electronics.

6. Periods abroad and/or in international research institutions

Remote collaboration (due to Covid-19 pandemic) with Prof. Pietro Tricoli, University of Birmingham, Birmingham (UK), in the framework of the abroad research period prescribed by the PON scholarship. The research activities carried out in collaboration with Prof. Tricoli focused on the Multi-Source Inverter power electronics converter and its potential in innovative power system architectures for multimode rail vehicles. Study and research activities included: preliminary bibliography research, mathematical modelling of the converter, analytical evaluation of its behavior under the state-of-literature control approach, numerical simulations, and experimental tests for validation of the theoretical analyses.
The remote collaboration with Prof. Tricoli covered a period of six months, from 1st December 2020 to 31st May 2021.

7. Tutorship

8. Plan for year three

The core of the research activity and resulting thesis in the third year will be focused on assessing the potential of the multi-source inverter for compact traction systems of light rail vehicles using onboard storage devices and alternative primary sources. In fact, the proposed modulation strategy led to promising results regarding the performance of multi-source inverters as compact single-stage solution in traction systems with multiple sources. Hence, further research efforts will be destined to its actual attractiveness in multimode electrified and catenary-less light rail vehicles that employ energy storage devices and alternative energy sources.
In case of catenary-less vehicles equipped with hybrid energy storage systems, the MSI-based architecture depicted in Fig. 7(a) operated with the MOVM algorithm will be compared to the standard architecture depicted in Fig. 7(b) in terms of control versatility, overall system performance and complexity.

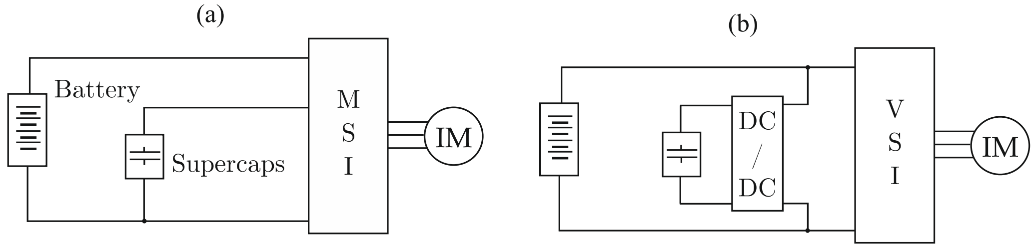
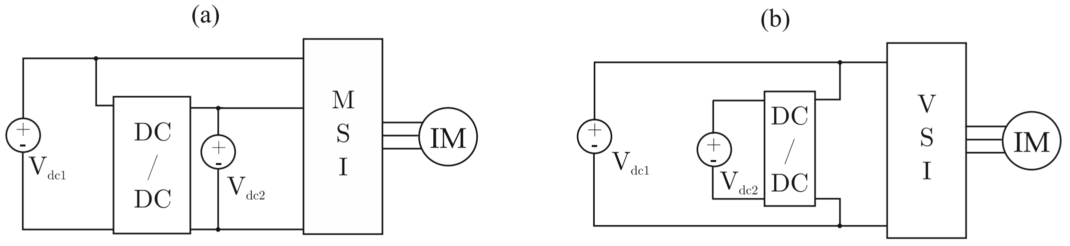


Fig. 7. MSI-based architecture (a) against standard architecture (b) for catenary-less rail vehicles supplied by onboard hybrid energy storage systems.

For electrified vehicles with overhead line connection and onboard storage devices, or catenary-less vehicles equipped with fuel cell systems and high-voltage batteries, the MSI-based configuration depicted in Fig. 8(a) will be compared to the standard solution of Fig. 8(b).



Electrified vehicles) Vdc1: overhead line; Vdc2: batteries or supercaps
Fuel cell vehicles) Vdc1: batteries; Vdc2: fuel cells

Fig. 7. MSI-based architecture (a) against standard architecture (b) for catenary-less fuel cell vehicles or electrified vehicles with extra onboard storage devices

For every configuration, the potential techno-economic attractiveness of the MOVM-controlled MSI architectures will be assessed by means of system-level simulations of real-case light rail traction systems and experimental tests on small-scale bimodal powertrains supplied by unidirectional and bidirectional DC sources. The comparison will mainly focus on the reduction in size or potential elimination of the main DC/DC converter, and its effects on the overall system volumes, costs, efficiency and complexity.
As side activity, further investigations will be carried out on the actual feasibility of bearing faults early detection using time-frequency analysis on motor voltages and/or currents. The activity will be mainly empirical and will allow to further understand if alternative diagnostic procedures that don’t use vibration measurements can yield sound and reliable diagnostic indicators.