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# Table of Contents

1 Table of Contents 2

2 Introduction 3

3 Training objectives 4

4 Research objectives 5

5 Key Performance Indicators (KPIs) 7

5.1 Technical KPIs 7

5.2 Non-technical KPIs 9

6 Dissemination activities 12

7 Intellectual Properties (IPs) 15

8 Future plans 16

9 Conclusion 17

# Introduction

The present report constitutes deliverable D4.2, a document produced in the framework of WP4 “Management and coordination”.

This deliverable reviews the achieved training and research objectives of the project. Then, D4.2 presents the key performance indicators (KPIs), including technical and non-technical KPIs. The technical KPIs evaluate the simulation models and the lab demonstrators of medium voltage DC electrification system and the power electronic traction transformer. The non-technical KPIs monitor the number of publications in international conferences, number of publications in international journals, and number of public transport stakeholders engaged to the project. Next, the deliverable summarises the dissemination activities, and reviews the developed intellectual properties (IPs) during the project. At last, D4.2 reveals the future plans and possibilities for the Project Consortium.

# Training objectives

The PhD student at Technical University of Cluj-Napoca had the opportunity to work and to complete a research project in the Applied Electronics department, to better understand DC-DC converters and to be prepared to present his results in various conferences. He learned to write and evaluate scientific articles and tackle different challenges, along with colleagues from the Renewable Energy research group.

The PhD student at University of Birmingham is pursuing his PhD at Department of Electronic, Electrical and Systems Engineering. He had the opportunity to be a part of power electronics group of Birmingham Centre for Railway Research and Education, where he gained valuable experience related to railway research and learned about high-power AC-DC power converters and medium voltage DC networks.

Both students accumulated experience in completion of an international research project, project management, and writing papers, reports, and deliverables (TO1) besides to their PhD studies. Furthermore, they arranged and participated in project meetings, which improved their teamwork skills. In April 2022, the project members from Technical University of Cluj-Napoca visited University of Birmingham and had a final meeting in person (TO3), to plan the final activities. The COVID-19 pandemic, however, prevented from holding more in person meetings and events.

The two early-stage researchers also participated in online and in person international conferences, where they had a chance to present their work, participate to the workshops, and establish a network with people from industry and academia (TO2). Following these events, the interested people to the project were invited to research meetings, as stated in section 5 in more detail (TO4). Arranging these meetings also helped the students to gain experience in organising meetings and events.

# Research objectives

In this project, a medium voltage DC (MVDC) railway electrification system with voltage level of 25 kV DC was proposed. Based on the requirements and specifications of the MVDC railway system, the converter topologies suitable for MVDC traction power substations (TPSs) were studied. As a result, modular multilevel converter with full-bridge submodules (MMC-FB) was chosen as a promising topology. In the next step, a more suitable modulation scheme for the MMC was designed and, on this basis, the DC fault current controller was successfully developed (RO1).

In the MVDC railway system, it is necessary to install power electronic traction transformers (PETTs) on the rolling stocks, to step-down the voltage of the MVDC catenary to the voltage level suitable for the motor drives.

To select a proper topology for the PETT and as a result of a detailed literature review, different high power density topologies of PETTs were described in the deliverable D2.1. These topologies are modular, based on silicon carbide (SiC) transistors, input-series-output parallel (ISOP) DC-DC converters with medium frequency transformers. Two bidirectional converter topologies were considered for the software model and experimental prototype: the dual active bridge (DAB) and the phase-shift full-bridge converter (PSFB). The full-scale simulation models of both topologies are presented in the deliverable D2.2 in detail. In the laboratory a 3-kW bi-directional PSFB evaluation board is available. The circuit was modified into a DAB topology. An exact simulation model of both variants of the converter was implemented and every experimental measurement was compared with simulation, for both topologies. The experiments were done on the 0-1000 W power range, with 350-400 V input voltage and 50 V output voltage. Both module prototypes operated well and produced similar waveforms as their simulation model under different load currents. Both topologies are suitable for the proposed application, however, DAB modules are simpler and a more cost-performance effective solution for the traction system (RO2).

As silicon (Si) semiconductors have reached their theoretical limits, new generation of semiconductors named wide band-gap (WBG) semiconductors have been emerged to replace with Si semiconductors. WBG semiconductors such as SiC, gallium nitride (GaN) and diamond are used to develop insulated gate bipolar transistors (IGBTs), metal oxide semiconductor field effect transistors (MOSFETs) and power diodes, which can improve the performance of both TPS and rolling stock power converters.

WBG semiconductors enable the power converters to operate in higher switching frequencies with higher energy efficiencies in comparison to their Si counterparts. Increasing switching frequency leads to decrease in size and volume of passive elements in the power converters. Specifically, the MMC-FB in the MVDC TPSs can be realised by smaller arm inductors. This increases the power density of the converter and saves space in the TPSs, which can be helpful when the cost of land for the TPSs is high. In addition, decreasing the capacitance required in the submodules makes it possible to replace the electrolytic capacitors with metalized polypropylene film (MPPF) capacitors, and increase the converter reliability.

In terms of efficiency and at the same switching frequency (converter volume), the use of WBG semiconductors in MMC-FB yields to higher efficiency, thanks to their lower on-state resistance and switching losses.

However, WBG semiconductors with high voltage ratings are still under development and are not commercially available. Therefore, at the current situation, the use of WBGs in MMC-FB yields to higher number of switches. In the deliverable D1.2, possible options for MVDC TPS converter topology using under developing SiC IGBTs have been analysed, showing trade-offs between the cost, number of components, reliability, efficiency, and control complexity.

The impacts and benefits of implementing WBG devices in PETTs were also examined and presented in the deliverable D2.1. In short, WBG semiconductors offer higher efficiency, better thermal characteristics and higher switching speeds with lower losses, which are beneficial for PETTs and increase their power density. The WBG devices are already used in traction converters of light rail vehicles, and future development of the technology will make them increasingly attractive for other traction systems as well (RO3). In D2.2 the study of their benefits was extended focusing on their impact on efficiency and power density. The results of the latest literature research demonstrated the significant benefits of SiC devices in different systems implemented by universities and the industry.

One of the challenges towards developing MVDC railways is to control and protect the MVDC network. Based on the simulation results presented in D1.2, the proposed MVDC electrification system can work well with a decentralised control approach, i.e., when each TPS has a reference voltage of 25 kV DC. This approach was tested successfully for a double-end fed system in the presence of PV farms, and also a meshed MVDC railway network.

In addition, a centralised control approach for a double-end fed MVDC railways was investigated. In this control scheme, the load is shared equally between the two TPSs. In this way, the installed capacity for each TPS can be decreased. However, there is a compromise between decreasing TPS installed capacity and the power losses in catenaries and running rails.

Moreover, a protection strategy was defined for the MVDC network. In this strategy, the MVDC TPS is protected by AC circuit breakers at the AC side. At the DC side, the TPS converter can limit the short circuit currents to a defined value, e.g., 120% of nominal DC current and then a low-power MVDC circuit breaker isolates the fault. If the fault is a non-permanent fault, i.e., the current becomes less than the defined value before the AC circuit breakers are tripped, the controller restores DC side voltage to nominal value and the converter continues to operate as normal. In a meshed MVDC network, all the TPSs can limit the short circuit current independently, so the MVDC network is fully protected against DC short circuit faults (RO4).

To find out about potential benefits of the storage systems in the MVDC railways, the on-board storage systems were studied in deliverable D2.1, reviewing the state-of-the-art technologies for storage and how it can increase the efficiency of the railway network. However, both TPS and rolling stock power converters in the proposed MVDC railways are bidirectional. This means that the excess energy from the trains’ braking can be injected back to the AC grid. Therefore, it was analysed that the addition of a bulky on-board energy storage is not a sensible idea for the MVDC railways and, thus, rolling stocks should be designed without on-board energy storage.

With reference to integration of renewable power sources in MVDC railways, it is sensible to have local energy storage systems in each TPS. This is because the power generation profile of renewable sources and the railway power consumption profile do not match, and the local energy storage system reduces the power mismatch (RO5).

To investigate the marketability of the MVDC electric railway system, the Project Consortium has had meetings and discussions with other Shift2Rail projects and industrial stakeholders. These activities are presented in more detail in section 5 (RO6).

# Key Performance Indicators (KPIs)

## Technical KPIs

**a) Railway electrification simulation tool**

a1) number of kilometres of lines simulated:

The developed model is able to simulate different scenarios with different line lengths and load conditions. The maximum time for the mentioned simulation cases is around 3 minutes. The simulations are done by a standard personal computer with the following properties:

Processor: Intel® Core™ i5-9500T CPU @ 2.20 GHz

Installed memory (RAM): 8 GB

Therefore, it is possible to simulate an infinite number of kilometres within different simulation cases.

a2) Transmission and converter power losses identified:

The loss analysis has been discussed in section 6.5 of D1.2. In addition, it is shown in D1.2 that the software model can successfully evaluate the transmission losses.

According to the estimated efficiency curve for MMC-FB, the efficiency at full load of 17 MW is 98.1%. Available efficiency curves for static converters which are based on MMC topology and designed for 16.67 Hz rail networks show that their efficiency is around 98.5% in quite similar conditions.

Therefore, the estimation of power losses from the model is within +/-20% of the values of similar converters developed for AC railways.

a3) Reduction of the design power of substations:

As stated in the simulation case of section 7 in D1.2, equal power sharing between two TPSs in a double-end fed railway can decrease the installed capacity for each TPS by 50%, i.e., from 20 MW to 10 MW. The second power converter for the MVDC substation lab demonstrator has not been developed due to lack of time. Therefore, it is not possible to monitor this KPI from the lab demonstrator.

**b) DC power electronics transformer**

b4) The overall specific volume occupancy [MW/m3]

The experimental small-scale module prototype of PETT has 4.34 kW/L or 4.34 MW/m3 power density. As additional reference, another bidirectional power converter module from the same manufacturer reached 3 MW/m3 (5.5 kW/kg). However, to better estimate the power density of a full-scale system, the state of the art literature was studied to find specific volume occupancy results on similar full scale systems and prototypes implemented by other research groups and the industry. In the transportation industry some papers present results up to 20 MW/m3 and even up to 40 kW/kg, using SiC devices and high performance inductors. Therefore, depending on the specifications, design and implementation technology, a specific volume occupancy between 10 and 20 MW/m3 is estimated for a full scale MVDC PETT.

b5) maximum harmonic distortion [%]

During the transients, the maximum of the PETT output voltage is 110% of the nominal value. In addition, the ripple at the output is less than 5%.

**c) Validation process**

c1) difference of the current drawn by the converter between experiment and simulation [%]

Considering MMC-FB lab demonstrator and as an example, the simulation model and the lab demonstrator are compared when a DC load of 0.5 A is applied to the converter. The comparison between amplitude of the phase currents at the input side of the autotransformer (415 V) shows a difference of around 0.1 A.

At the output side of the autotransformer, the Fourier analysis of the phase current of the lab demonstrator illustrates that there are negligible harmonic contents around the switching frequency (5 kHz).

Considering the DC bus voltage, the DC voltage provided by the lab demonstrator has the average of 344 V with peak to peak ripple of 6 V (1.74%). In the simulation model, the average of DC voltage and its peak to peak ripple are 350 V and 5 V (1.43%), respectively.

The differences are due to the approximations made in the simulation model and the difference between the entered parameters in the simulation and the actual values in reality.

In the case of the PETT, different parameters were monitored: output voltage ripple, resonant inductor current and output current. For the Dual Active Bridge topology an output voltage ripple between 2.5% and 3.3% was obtained in the simulation model of the experiment prototype and 5% ripple on the oscilloscope in the actual experiment. The maximum difference between the currents measured in simulations compared to the experimental tests for different load scenarios was 5%-10%. Since the output parameters are DC, the harmonic distortion is irrelevant. In the case of the Bidirectional Phase-Shift Full-Bridge converter the maximum difference between currents was around 10% at maximum load and up to 5% for light loads. The ripple on the output voltage is only 300 mV of 50 V (0.6%) for constant power. In different load scenarios with varying power the ripple reaches a maximum of 10% (5 V peak to peak). In the simulation the output voltage ripple was negligible.

c2) time response of the control loop

MMC with full-bridge submodules has been selected to be used in the TPSs and the size of its passive elements for the simulations and the lab demonstrator have been determined. The simulation cases stated in the deliverable D1.2 show that the DC short circuit current controller can limit the fault current within 370 µs and after that, the mean value for the current is less than IDC,max = 120% of nominal DC current. Therefore, the KPI objective has been achieved in the simulation model. The DC short circuit current controller has not been tested on the lab demonstrator due to lack of time.

## Non-technical KPIs

**a) Number of publications in international conferences**

The published conference papers and poster presentations are as follows:

* Ferencz, D. Petreus, and P. Tricoli, “Converter topologies for MVDC traction transformers,” in 2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME), October 2020, pp. 362–367, doi: 10.1109/siitme50350.2020.9292214. <https://research.birmingham.ac.uk/portal/files/103293345/SIITME2020_Ferencz.pdf>

(Poster presentations)

[https://1drv.ms/b/s!AvGiGYFHnSC6lGPn8gw2bgxwyI4e?e=reaHGE](https://1drv.ms/b/s%21AvGiGYFHnSC6lGPn8gw2bgxwyI4e?e=reaHGE)

[https://1drv.ms/p/s!AvGiGYFHnSC6lGQAYUG2mCyjpr1X?e=m00j7p](https://1drv.ms/p/s%21AvGiGYFHnSC6lGQAYUG2mCyjpr1X?e=m00j7p)

[https://1drv.ms/u/s!AvGiGYFHnSC6lGVSX\_BbnKPPUduU?e=Ndn2oh](https://1drv.ms/u/s%21AvGiGYFHnSC6lGVSX_BbnKPPUduU?e=Ndn2oh)

* Ferencz, D. Petreus and T. Pătărău, "Comparative Study of Three Snubber Circuits for a Phase-Shift Converter," 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2020

<https://www.researchgate.net/publication/344175619_Comparative_Study_of_Three_Snubber_Circuits_for_a_Phase-Shift_Converter>

* Ferencz, D. Petreus, and P. Tricoli, “A Power electronic traction transformer for a medium voltage DC electric railway system,” in 2021 IEEE 44th International Spring Seminar on Electronics Technology (ISSE), May 2021. <https://research.birmingham.ac.uk/portal/files/134995975/D06_PAPER.pdf>
* S. Sharifi, T. Kamel, P. Tricoli, “Investigating the best topology for Traction Power Substations (TPSs) in a Medium Voltage DC (MVDC) railway electrification system”, 23rd European Conference on Power Electronics and Applications (EPE21), September 2021.

<https://research.birmingham.ac.uk/en/publications/investigating-the-best-topology-for-traction-power-substations-tp>

(Poster) <https://onedrive.live.com/?authkey=%21AENFhUKD150sPQQ&cid=BA209D478119A2F1&id=BA209D478119A2F1%212669&parId=BA209D478119A2F1%212658&o=OneUp>

(Dialogue presentation)

<https://onedrive.live.com/?authkey=%21AOMlbo56RGBoBU0&cid=BA209D478119A2F1&id=BA209D478119A2F1%212668&parId=BA209D478119A2F1%212658&o=OneUp>

* Sina Sharifi, P. Tricoli, C. Roberts, “Flexible Medium Voltage DC Electric Railway System,” in Centre for Power Electronics (CPE) Annual Conference, July 2021, poster presentation.

<https://onedrive.live.com/?authkey=%21ANmWgNdmiecSNU8&cid=BA209D478119A2F1&id=BA209D478119A2F1%212662&parId=BA209D478119A2F1%212658&o=OneUp>

* Sina Sharifi and P. Tricoli, “Medium voltage DC (MVDC) railway electrification systems: Assessment of performance,” in World Congress on Railway Research 2022, June 2022.

<https://research.birmingham.ac.uk/en/publications/medium-voltage-dc-mvdc-railway-electrification-systems-assessment>

(Poster)

[WCRR2022\_Poster\_Medium voltage DC (MVDC) railway electrification systems](https://1drv.ms/b/s%21AvGiGYFHnSC6mxbvsuQAtVuBd_K9?e=AejwRz)

(Presentation)

[WCRR2022\_Presentation\_Medium voltage DC (MVDC) railway electrification systems](https://1drv.ms/p/s%21AvGiGYFHnSC6mxXieidD8RbV6iJ3?e=3r468c)

In addition, one paper has been submitted for a presentation:

* Ferencz, D. Petreus and T. Pătărău, “Small-Scale DC PETT Module Prototype for the Novel 25kV MVDC Electric Railway System”, 16th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2022), June 2022.

**b) Number of publications in international journals**

* I. Ferencz, D. Petreus, "A Power Electronic Traction Transformer Model for a New Medium Voltage DC Electric Railway," Advances in Electrical and Computer Engineering, vol.21, no.3, pp.99-108, 2021.

<https://aece.ro/abstractplus.php?year=2021&number=3&article=12>

In addition, one other journal paper has been submitted and the authors are waiting for the review process.

**c)** **Number of public transport stakeholders engaged to the project**

As mentioned in section 5, the following groups have participated to the events/meetings related to the project:

1. Manufacturers/Companies:
* Siemens
* Hitachi-ABB power grids
* Gemini Rail Group
1. Transport operators
* SNCR Réseau, France
* Network Rail, UK
1. Professional associations
* UIC, France
1. Academic institutions
* EPFL, Switzerland
* Laplace, Institut National Polytechnique de Tolouse, France,
* Politecnico di Milano, Italy

#  Dissemination activities

To disseminate the project results and engage industrial and scientific communities, the project webpage (<https://www.birmingham.ac.uk/mvdc-ers>) was created. The webpage was kept updated with the project leaflet, public deliverables, newsletters, and publications. The twitter account (<https://twitter.com/PietroTricoli>) and LinkedIn account (linkedin.com/in/pietro-tricoli-b8ab278) were also used for dissemination purposes. In addition, the project team presented the project in different events/meetings, as summarised in Table 1. It is noteworthy to mention that the restrictions due to COVID-19 pandemic caused limitations in holding in-person events since January 2020.

It was also found that the project has good synergies with the other Shift2Rail projects Fundres, in the area of MV DC railways, and In2Stempo, in the area of power converters for railway feeder stations. The first workshop of the project was organised with representatives of MVDC-ERS, FUNDRES and IN2STEMPO in June 2021. All the partners of these consortia took part to the event and it was shown a good level of interest in progressing the discussion for a potential demonstrator for the successor of Shift2Rail. More information about this joint event can be found in this newsletter (<https://www.birmingham.ac.uk/documents/college-eps/eece/research/shift2rail-projects-mvdc-ers-fundres-ins2tempo-joint-newsletter-oct-21.docx>).

Table 1 - Participated events and meetings by MVDC-ERS members

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Lead partner | Type of event | Event title | Date(s) | Place | Link | Partner contribution | Countries addressed | Target audience |
| UoB | Conference | 7th International Conference on Clean Electrical Power | 2nd to 4th July, 2019 | Otranto, Italy | <https://www.iccep.net/> | Presenting the project | Worldwide | Scientific and industrial community |
| UoB | Community event | Destination Decarbonisation Event | 17th Sep. 2019 | Quinton Rail Technology Centre, Quinton, UK | <https://blog.bham.ac.uk/bcrre/2019/09/23/destination-decarbonisation/> | presenting the project | UK | Industrial community |
| UoB | Exhibition and conference | Modern railways RVE show | 3rd October, 2019 | Derby, UK | <https://rve-expo.co.uk> | Visiting the exhibition and discussing the project | EU countries | Railway stakeholders (technology providers) |
| UoB | Meeting | Meeting with head of Engineering Technology of Gemini Rail Group | 28th Jan 2020 | Birmingham, UK | <https://www.geminirailgroup.co.uk> | Presenting the project - discussion on possible ways for collaboration | - | Industrial community |
| UoB | Workshop | Decarbonising Transport through Electrification Network+ | 26th February 2020 | Cardiff, UK | <https://dte.network/dte-launch-event> | Presenting the project | UK | Scientific and industrial community |
| TUCN | Conference | 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) | 24th-26th June 2020 | Online conference | <http://www.speedam.org/> | Power point presentation of the paper | Worldwide | Scientific Community |
| TUCN | Conference | 2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME) | 21st-24th October 2020 | Online conference | <http://siitme.ro/> | Video pitch presentation of the poster and project | Worldwide | Scientific Community |
| UoB | Conference | High Speed Rail: Education Interchange Conference | 14th Dec. 2020 | Online conference | <https://www.birmingham.ac.uk/research/railway/events/2020/hsrei-2020/high-speed-rail-education-interchange-2020.aspx> | Presenting the project and networking with stakeholders | Worldwide | Scientific and industrial community |
| UoB | Meeting | Meeting with FUNDRES project | 15th February 2021 | Zoom meeting | <https://fundres-project.eu/> | Presenting the project - discussion on possible ways for collaboration | - | Scientific Community |
| UoB | Online paper | Publishing an article | May 2021 | Global Railway Review website | <https://www.globalrailwayreview.com/article/119629/mvdc-ers-railway-electrification-systems/> | Publishing a short article about the project | Worldwide | Industrial community |
| TUCN | Conference | 2021 IEEE 44th International Spring Seminar on Electronics Technology (ISSE) | 5th-7th May 2021 | Online conference | <https://www.isse2021.net/isse-2021> | Power point presentation of the paper and project | Worldwide | Scientific Community |
| UoB | Online meeting | Meeting with Head of Power Systems Engineering and Innovation at SIEMENS Mobility UK | 15th June 2021 | Zoom meeting | <https://www.mobility.siemens.com/uk/en.html> | Presenting the project | - | Industrial community |
| UoB and TUCN | Webinar | FUNDRES, IN2STEMPO and MVDC-ERS Joint event (Midterm workshop) - Smart railway traction power supply | 29th June, 2021 | Online Webinar | <https://www.birmingham.ac.uk/documents/college-eps/eece/research/shift2rail-projects-mvdc-ers-fundres-ins2tempo-joint-newsletter-oct-21.docx> | Presentations | EU countries | Shift2Rail projects working on the traction power infrastructure |
| UoB | Conference | Centre for Power Electronics (CPE) Annual Conference | 13th - 15th July 2021 | Online conference | <https://www.powerelectronics.ac.uk/events/annual-centre-for-power-electronics-conference/?ct=t(EMAIL_CAMPAIGN_9_30_2020_14_21_COPY_01)&mc_cid=084f324851&mc_eid=5a5e45bf77> | Poster presentation about the MVDC-ERS research | UK | Scientific and industrial community |
| UoB | Conference | 23rd European Conference on Power Electronics and Applications (EPE21 ECCE Europe) | 6th - 10th Sep. 2021 | Online conference | <http://www.epe2021.com/> | Presenting a dialogue presentation - networking activities | EU countries | Scientific and industrial community |
| UoB | Online meeting | Meeting with Hitachi ABB power Grids | 30th Sep. 2021 | MS Teams meeting | [www.hitachiabb-powergrids.com](http://www.hitachiabb-powergrids.com/)  | Presenting the project - discussion on possible ways for collaboration | - | Industrial community |
| UoB | Open Day event | UK Rail Research and Innovation Network (UKRRIN) Open Day | 20th October 2021 | University of Birmingham | <https://www.ukrrin.org.uk/> | Presenting the project | UK | Scientific and industrial community |
| UoB | Conference | IEEE Vehicular Power and Propulsion 2021 (IEEE VPPC 2021) | 25th - 28th October, 2021 | Gijón, Spain | <https://events.vtsociety.org/vppc2021/> | presenting the project and networking with stakeholders | Worldwide | Scientific and industrial community |
| UoB | Away day | Atkins away day | 11th May 2022 | University of Birmingham |  | Presentation of the project | UK | Industrial community |
| UoB | Conference | World Congress on Railway Research (WCRR) 2022 | 6-10th June 2022 | International Convention Centre Birmingham, United Kingdom | <https://www.wcrr2022.co.uk/website/938/homepage/> | Interactive presentation of a paper | Worldwide | Scientific and industrial community |
| UoB | Lab tour | World Congress on Railway Research (WCRR) 2022 - BCRRE lab tour | 10th June 2022 | University of Birmingham | <https://www.wcrr2022.co.uk/website/938/homepage/> | Presenting the project | Worldwide | Scientific and industrial community |
| TUCN | Conference | 2022 CPE-PowerEng – 16th IEEE International Conference on compatibility, Power Electronics and Power Engineering | 29th June-1st July 2022 | University of Birmingham | <https://uobevents.eventsair.com/ieee2022/> | presenting a paper | Worldwide | Scientific Community |

# Intellectual Properties (IPs)

1. The MVDC railway simulator:

The MVDC railway simulator has been developed in Matlab/Simulink environment. It mainly consists of MVDC traction substations (TPSs) and MVDC overhead lines. Each TPS consists of modular multilevel converter with full-bridge submodules and the distribution network model. The model is able to estimate the losses of the TPS converter. It is also possible to simulate an individual TPS with MMC with half-bridge submodules.

The railway simulator can simulate double-end fed and meshed MVDC networks. The model is also able to simulate the double-end fed MVDC network in the presence of PV farms. In double-end fed MVDC network, it is possible to implement and test a power sharing scheme.

The developed model is a tool that can be used by the railway operators for assessing MVDC network performances in various scenarios. Currently, this IP is being used for the further research and analysis.

2. A method for controlling and modulating modular multilevel converters with full-bridge submodules:

The developed control and modulation method for MMC-FB enables the converter to operate with low DC side ripples (in rectifier mode of operation), unity power factor and acceptable voltage ripple across the submodule capacitors. The method is especially beneficial for MVDC MMC-FBs which have low number of submodules. The method has been implemented and tested on the MVDC TPS converters.

The method can be used in medium voltage MMC-FBs in different applications (such as MVDC distribution network, electric ships, etc.) to provide high quality voltage and currents at both DC and AC sides. In addition, simpler and cheaper MVDC circuit breakers are enough for DC side protection, thanks to the DC short circuit current limiting control. Currently, this IP is being used for the further research and analysis. For future use by industry, it needs to be tested on the hardware (in progress). It possibly needs some enhancement on controlling circulating currents.

# Future plans

The PhD student at UoB will submit his thesis to complete his PhD studies in 2022. MVDC-ERS project and PhD degree will provide opportunities for him to either work as a research fellow at universities or continue his carrier in industry worldwide. Based on his previous study background and the experience gained in MVDC-ERS project, he is able to work in the fields of power electronics, railway electrification systems, power system studies, renewable energies, and smart grids.

The PhD student at TUCN will submit his thesis in the summer of 2022. The valuable experience obtained in this project will help him to find opportunities in the industry and other research collaborations. His previous study and research background allows him to work in different fields such as electronics, power converters, renewables, and transportation systems. MVDC-ERS offered him a good insight in how an international project works and thus encouraged him to take part in such works in the future with more confidence.

During the project, a group of people from industry and academia were contacted and informed about the MVDC-ERS research. There will be also possibilities for further discussions, seeking for opportunities to continue research in MVDC railway area or contribute to other research areas, including Europe’s Rail research programmes.

# Conclusion

This deliverable has reviewed the effect of the project by summarising activities of the project team. First, it has presented the training objectives and the experience gained by the early-stage researchers. In addition, it has briefly described the achieved research objectives.

In addition, the deliverable has evaluated technical key performance indicators (KPIs) related to the simulation models and the small-scale experimental setups, together with non-technical KPIs, which monitor the number of conference and journal publications, and engagement of stakeholders.

Furthermore, the document has presented the events and meetings related to the MVDC-ERS project, which helped the project team to establish a network with academic and industrial community.

In addition, the deliverable has described the intellectual properties (IPs) developed during the project and their status.

At last, the document has introduced the future plans and opportunities for the Project Consortium.