FUNDRES

FUTURE UNIFIED DC RAILWAY ELECTRIFICATION SYSTEM

Newsletter

Issue 1, February 2021

FOREWORD

The Shift2Rail-funded project FUNDRES is a €0,75 million project led by LAPLACE (Laboratory of plasma and conversion of energy, University of Toulouse) in collaboration with three other European partners namely: the Politecnico di Milano, the Ecole Polytechnique Fédérale de Lausanne and the International Union of Railways.

Project partners have already made considerable achievements within the first year. We will present in this newsletter the main goals of the project and some of the results achieved during the first year of the project.

For more information about FUNDRES, consult our website or contact Ms. Christine HASSOUN at: hassoun@uic.org.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 881772

FACTS & FIGURES

EU contribution
€750 000

Duration
24 months

Project Start Date
01/12/2019

Project End Date
30/11/2021

Partners
4 from 3 countries

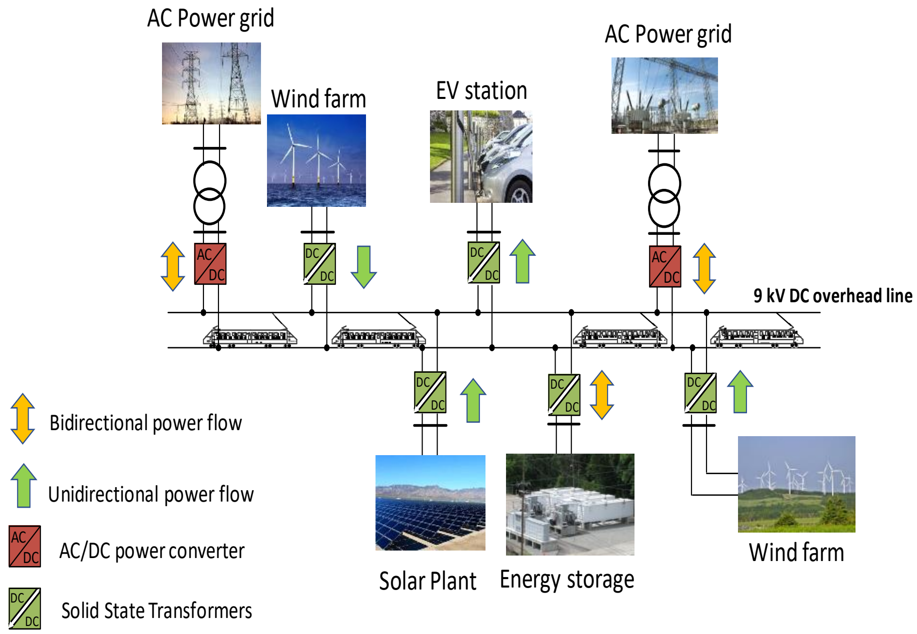
Grant agreement
n°881772

Project coordinator
LAPLACE

Website:
fundres-project.eu

SUMMARY

One of the main challenges of the rail sector is to increase traffic while improving energy efficiency and limiting environmental impacts. The FUNDRES project proposes to define a future unified DC railway electrification system which could become a new standard in Europe. The use of Medium Voltage DC allows an efficient power supply of rolling stock and constitutes, on a large scale, the backbone of a network integrating renewable sources, storage elements and charging stations for electric vehicles.



PROJECT STRUCTURE

WP Number	WP Title	Lead beneficiary
WP1	Management	Institut National Polytechnique de Toulouse (LAPLACE)
WP2	Grid interaction Railway power supply and public grid	Ecole Polytechnique Fédérale de Lausanne (EPFL)
WP3	Integration of renewable sources, storage systems and charging infrastructures in 9 kVDC railway system	Politecnico di Milano (POLIMI)
WP4	Solid State Transformer	Institut National Polytechnique de Toulouse (LAPLACE)
WP5	Communication, dissemination and link with other projects of S2R	International union of railways (UIC)

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CHALLENGE

Regarding the energy challenge for the railway sector, the project FUNDRES presents a deep forward thinking scenario and proposes related work to define the future of railway.

FUNDRES focuses on a Medium Voltage DC electrification system that can serve as energy hub for renewable sources in order to:

- increase the capacity while improving the energy consumption and limiting the environmental impacts
- decrease the investment and exploitation costs, while maintaining safety and service quality

MAIN OBJECTIVES

FUNDRES project

01 **Quantify** potential impact of the increase in voltage levels in DC railway electrification

02 **Explore** suitable power supply schemes with renewable sources and impact of power electronics and energy storage technologies, as well as interactions with 3-phase utility grids in ancillary service markets

03 **Deliver** modelling tools to simulate all relevant scenarios and to implement Digital Twins, both at equipment level and system level

04 **Set up** representative experimental demonstration to evaluate performances of the future DC system, focusing on 9kVdc as an example

05 **Give** recommendations for the new future unified DC railway power supply to the project's advisory group, to the members of Shift2rail's Innovation Programme n°3, to standardisation committees

WP2 GRID INTERACTION RAILWAY POWER SUPPLY AND PUBLIC GRID

Task Leader: EPFL

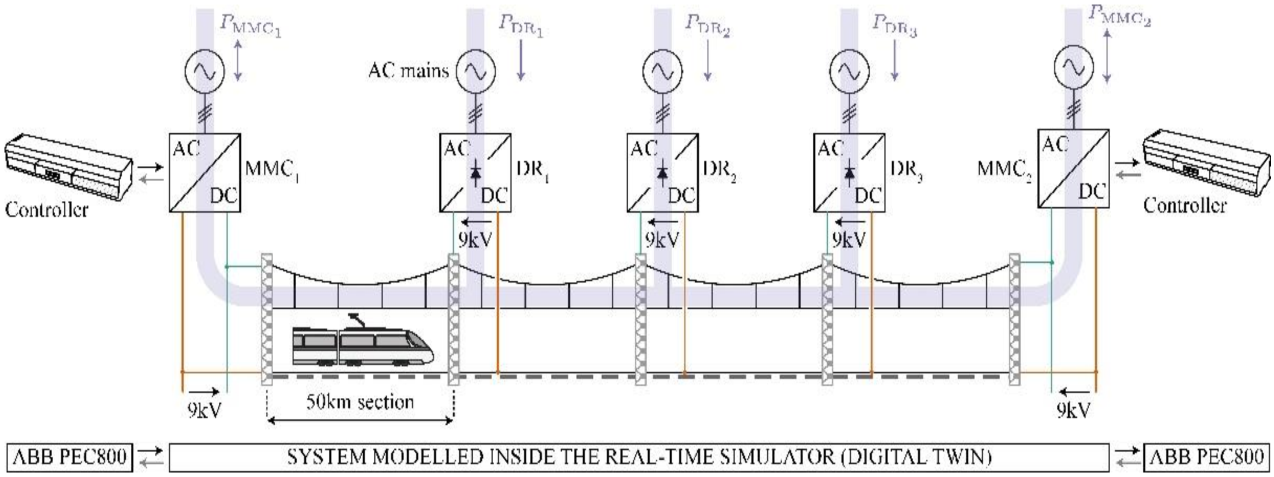

Fig. 1 *Test scenario adopted to explore the 9kV$_{dc}$ supply system with active, MMC-based bi-directional substations.*

Fig. *1* depicts the test scenario adopted for the WP2, in order to quantify performances of the 9kV$_{dc}$ system employed in the railway lines. An exemplary 200km line segment, divided into four 50km long sections, is considered. In between the sections, Diode Rectifiers (DRs), representing a traditional and a well-known substation solution, allowing solely for a unidirectional power flow, are installed, while the ends of the observed line segment are supplied by two Modular Multilevel Converters (MMCs). Such a configuration is expected to provide an outstanding flexibility in terms of the load flow control, owing to the bidirectional nature of the MMCs. What is more, in contrast to the DR, being passive device providing a DC voltage of only one polarity, the MMC offers fast-dynamic control of its DC voltage allowing for voltage of both polarities to be synthesized. Such a feature proves to be extremely beneficial during faults (e.g. short circuits) in the network the MMC operates in, therefore, resilience of the system presented bellow becomes immensely increased.

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Real-time simulations of the system from **Fig. *1*** will be carried out by means of the MMC Digital Twin presented in **Fig. *2***, which will be further extended by the railway network model. As can be seen from **Fig. *2*a**, seven RT Box 1 units from PLEXIM, were connected, synchronised and operated together, for the first time, in order to create the environment suitable for the real-time emulation of one MMC. The so-called Branch RT Box, which is replicated six times, captures the switching signals, originating from the controller used on the real power hardware, of the converter stage it is associated with. Further, Application RT Box provides the environment for real-time simulation of a surrounding network. As the abovementioned test scenario requires two MMCs, two Digital Twins, as presented in **Fig. *2***, will be operated in parallel to host the model of two MMCs combined with the elements, such as railway lines and DRs, depicted in **Fig. *1.***

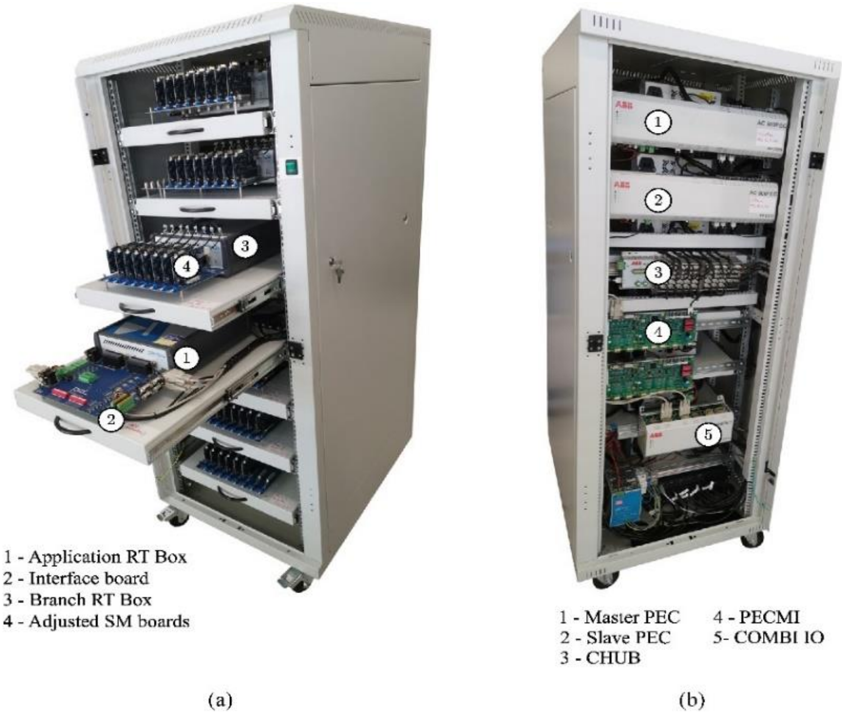

Fig. 2 Digital twin of a single MMC realized by means of the small-scale HIL units (RT Box). (a) front view; (b) rear view.

To make all the results reliable and realistic, the developed Digital Twin is combined with industrial ABB PEC800 controllers, as can be seen **in Fig. *2***. Two ABB PEC800 controllers can be recognised and they are connected in the Master/Slave structure. The main reason for such a configuration lies in the fact that several of these HIL systems can be connected to operate in various configurations, which is exactly the need in this case. Each Slave controller is assigned the task of controlling its associated MMC, while one Master controller is to handle general (application) state machine and references. Other parts of the system visible in **Fig. *2*** are in the charge of voltage/current measurements (PECMI), distribution of SM optical signals (CHUB) and manipulation of relays, switches and other user defined arbitrary signals (COMBIO). It must be emphasized that the real MMC prototype at Power Electronics Laboratory at EPFL, uses the identical control structure, making the presented HIL attractive and reliable from the standpoint of the presented test scenario verification.

WP3 SMART 9 KV DC RAILWAY SYSTEM: INTEGRATION OF RENEWABLE SOURCES, STORAGE SYSTEMS AND CHARGING INFRASTRUCTURES

Task Leader: POLIMI

State of the art of smart electric railway grids

In recent years, the achievement of sustainable energy systems has become one of the foremost challenges of experts all around the world. Environmental concerns like global greenhouse gas emissions and other problems related to fossil fuels together with deficiency of its resources are other significant aspects. The emergence of smart grid (SG) concept as the developing next generation of electricity grid has exposed the impressive capabilities and opportunities of reducing mentioned emissions, energy consumption, and customer costs together with improving energy efficiency, reliability, and safety. It has provided a great path of evolution towards more sustainable technologies comprising renewable energy sources (RES). Given the fact that electric railway systems (ERSs) are known as one of the huge and high consumption end-users in the utility grid, the implementation of SG innovations and technologies in such large systems are considered as an effective and indispensable issue. However, despite the increasing developments and tremendous progress of SG in the utility power network and other industry sectors, it is retarded in ERSs. While ERSs have a high potential to be adapted with SG technologies due to dedicated equipment and lines in transmission and distribution parts. Meanwhile, instead of substantial replacement of railway infrastructure, it requires to be investigated about the convenient integrating points and methods.

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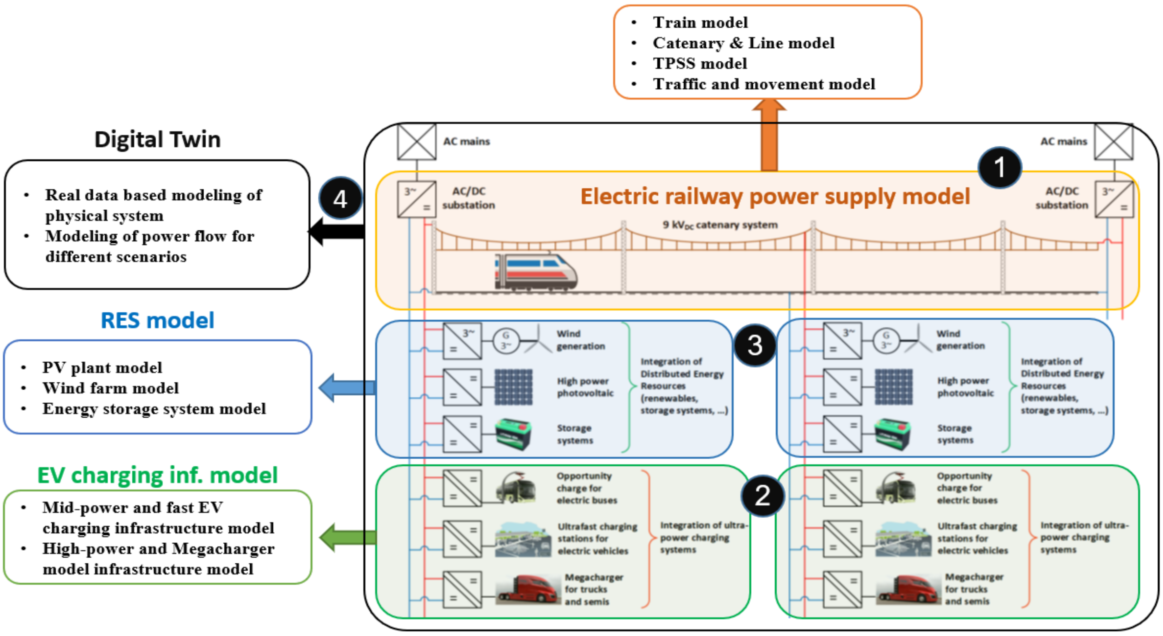

Fig. 3: *Proposed smart MVDC ERS outline.*

Towards smart MVDC electric railway grid

Unlike the low voltage DC ERSs, the implementation of SG concept especially for MVDC ERSs has not been paid much attention. While, the high power capability of MVDC ERSs facilitates the direct connection of RESs such as wind farms and wide-scale photovoltaics without any conversion to ac power or voltage level changing. Furthermore, from the EV charging infrastructures point of the view, MVDC ERSs can allow for fast and ultrafast charging stations that could be problematic if they are connected to the AC mains for their power absorption. In the scenario proposed in FUNDRES, the proposed smart ERS comprises incorporating of RES, as PV array and wind generation, using regenerative braking energy together with railway power flow controller and energy storage systems (ESS), as well as charging infrastructures for electric vehicles (EVs). The outline of proposed system is shown in **Fig. 3**. The whole system has been divided into three subsections including electric railway power supply model, RES integration models and charging infrastructures model which are simulated and modified by the algorithm to accept real data from physical railway system as a digital twin.

Electric railway power supply model

To have an exact model of an electric railway power supply system, different parts including overhead catenary and line, train electric circuit, traction power substation (TPSS) and train movement must be modelled precisely. Therefore, to extract and analyse current distribution of system, a hierarchical algorithm as shown in **Fig. 4** is implemented. Voltage profile of line, power and current calculation in TPSS and different nodes together with voltage drop along the line are the outputs of this method. The proposed algorithm is implemented for a real case study of Rome-Florence high-speed line.

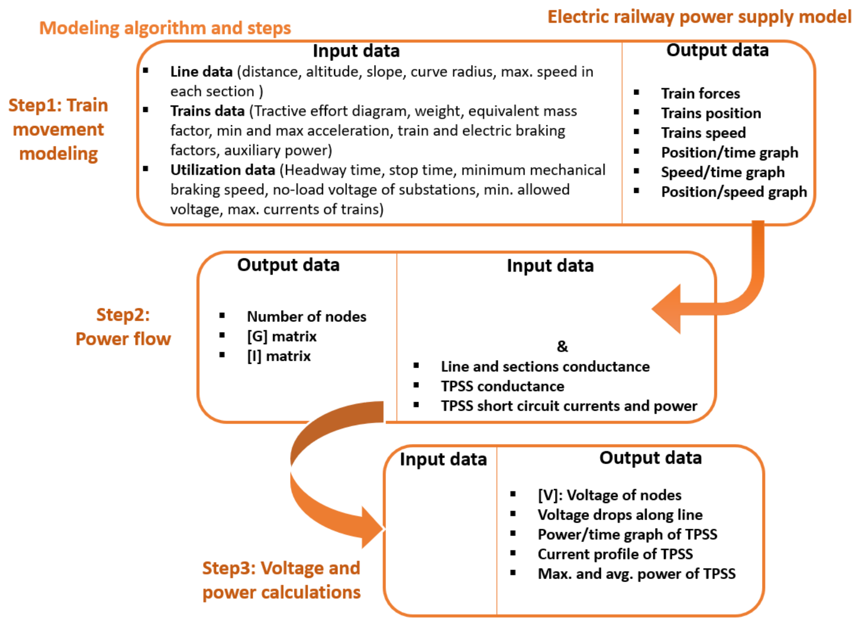

Fig. 4: Electric power supply modelling flowchart.

Renewable energy sources (RES) model

To import an accurate model of RES, based on the annual irradiance-temperature and wind speed maps of Italy (around the Rome-Florence line), a realistic model of irradiance-temperature and wind speed are modelled according to the **Fig. 5**. Consequently, the most important factors as power range of plants, module type, numbers and their connection type and MPPT control method are assigned considering the proposed high-speed 9 kV capabilities.

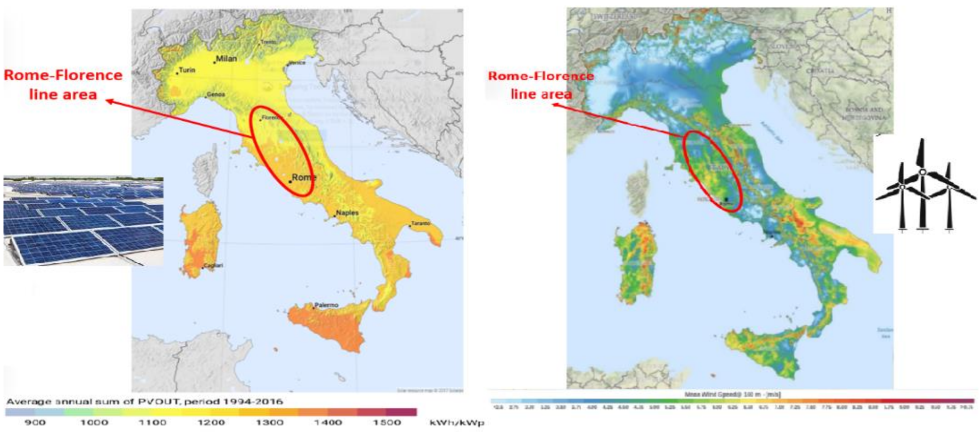

Fig. 5. *Annual maps of irradiance-temperature and wind speed.*

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EV charging infrastructures model

The high-power capabilities of the proposed 9 kV DC system allows for fast and ultrafast charging stations that could be problematic if they are connected to the AC mains for their power absorption. In the FUNDRES scenario, due to the presence of a DC grid, only mode 4 DC charging infrastructures has been considered, since there is no sense the DC/AC conversion for low power charging stations. In any case, mode 4 charging systems are available for a wide power range. Accordingly, four topologies as **Fig. 6** have been studied to be connected to the MVDC ERS. Extracting the charging profile based on arrival, departure and connecting times for topologies and finally extracting output power/current-based model to be connected to 9 kV DC have been carried out.

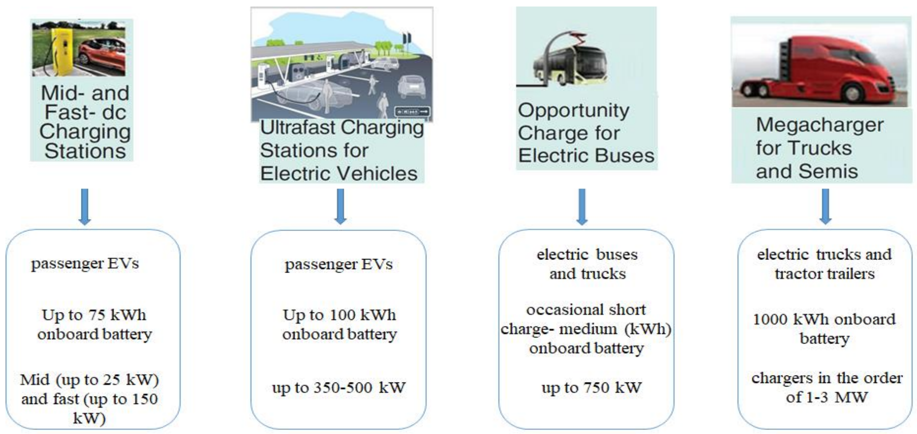

Fig. 6. *Different topologies of charging infrastructures.*

Digital twin implementation

According to the obtained results from simulations of final extracted model, we are modifying the algorithm to accept real data from physical railway system as contribution of digital twin. In this context, the under study algorithm shown in **Fig. 7** will get some real data including real train positions, speed and some other traffic and line information as inputs. The output power flow analysis in different contributed scenarios will result as the state estimation of system to some applications like providing prediction for any destruction to the electric equipment, faults diagnosis, transient events, maintenance, impacts of RES, conditioning peak power/overload situation of system and sizing ESS and interface converters.

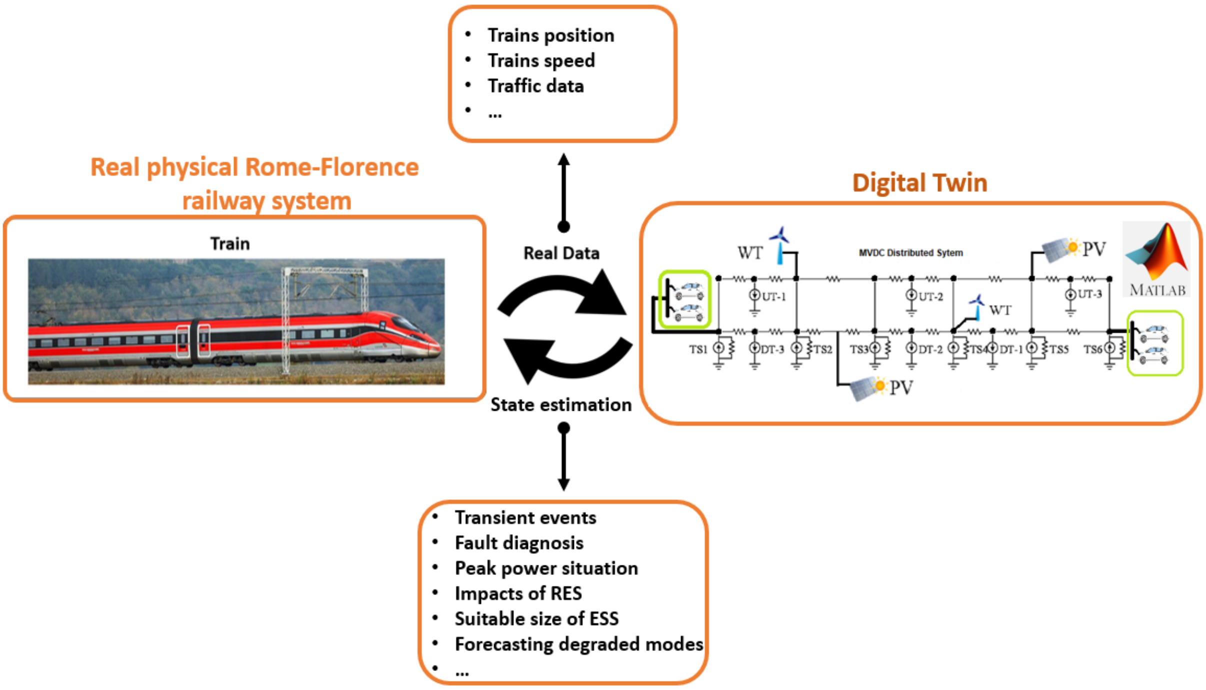

Fig. 7. *General scope of implementing digital twin for proposed 9 kV DC railway line.*

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WP4 SOLID STATE TRANSFORMER

Task Leader: LAPLACE

State of the art of the railway electrification systems

In European Union, three electrification systems are mainly used: DC (1.5 kV or 3 kV), MVAC at special frequency (15 kV / 16.7 Hz) and MAVC at industrial frequency (25 kV / 50 Hz). The first two systems were introduced at the beginning of the 20th century. The last one was developed by French Railways after the Second World War. Nowadays in EU, the distribution of electrified lines is as follows:

DC°: °47 000 km; MVAC 15 kV/16.7 Hz: 33 000 km; MVAC 25 kV/50 Hz: 28 000 km.

Regarding the DC electrification system, only 20 % of the lines are electrified in 1.5 KV (mainly in France and Netherland) and 80 % in 3 kV. Today's DC electrification systems suffer from a relatively low voltage level that limits locomotive power and traffic density due to the high currents in the overhead-line. Thanks to the medium voltage level, AC electrification systems allow the use of overhead lines with small cross-sections. The voltage drop is mainly related to the reactance of the traction circuit and reactive power compensation means are sometimes used to boost the line voltage. The 25 kV/50 Hz system is the most penalized from this point of view. The 15 kV/16.7Hz system requires a specific power supply network but allows, as in the DC system, a parallel connection of the substations. In the 25 kV / 50 Hz system, single-phase substations require high short-circuit power at the connection point to avoid voltage unbalances on the three-phase grid. Therefore, substations must be equipped with unbalance compensation systems or connected to 220 kV or 400 kV high-voltage lines. Regarding the rolling stock, modern AC locomotives include a single-phase step-down transformer, a rectifier, a low-frequency filter (tuned to 33.4 Hz or 100 Hz), and a three-phase voltage source inverter that supplies the AC traction motor. On the other hand, the on-board traction converter of a DC locomotive is much simpler and is reduced to an input filter and a three-phase voltage source inverter.

Towards a future unified DC electrification system

Nowadays, research laboratories, electrical network operators, and manufacturers of electrical equipment are seriously considering the use of DC in electrical power distribution. Indeed, renewable energy sources and associated storage devices are simpler to integrate into a DC grid. Thus, new concepts concerning the development of clusters in medium-voltage direct current (MVDC) are emerging. The same concept can be envisaged for railway electrification and it is obvious that a DC electrification with a higher voltage combines the favourable aspects of existing electrification systems discussed previously. DC benefits from the absence of inductive voltage drop, the absence of reactive power, the absence of voltage unbalance at the grid connections and the simplification of the traction chain. A higher voltage level allows the use of a light overhead-line and a reduced number of substations.

This MVDC electrification system constitutes, on a large scale, the backbone of an electrical energy hub and distribution network integrating renewable sources and storage elements. The connection points to the three-phase public grid are already available in the existing substations. Reversible AC/DC converters can be installed and offer ancillary services to the grid operator. In the scenario proposed in FUNDRES, Solid State Transformers (SSTs) play a major role since they allow to interface the different energy sources and the storage elements.

Study of reinforcement of a 1.5 kV electrification system by a 9 kV feed-wire

The implementation of a the new MVDC power supply seems conceivable within a few years in countries where the electrification of railways is still to be fully developed. In European countries which already use DC electrification systems, it cannot be envisaged in the short term. It is indeed impossible to simultaneously modify the rolling-stock and the infrastructure. Thus, this section proposes a solution to carry out, in a short-time, the switchover from conventional electrification at 1.5 kV DC to 9 kV DC. The objective is to increase the capacity of a railway line by allowing the circulation of more powerful locomotives. The initial power supply is preserved and an additional MVDC feed-wire is installed. Stepdown SSTs are used to reinforce the power supply of the trains.

This scenario could apply to a line of the French rail network which, in years to come, could be dedicated mainly to freight traffic with trains from 1,600 tonnes to 2,400 tonnes. To move the freight trains at a speed of 120 km/h, Multiple-Unit of two locomotives are used and the power absorbed by each train can reach 8 MW.

The principle of the reinforcement is illustrated in **Fig. 9**. We have considered a typical substation spacing of 15 km. Each sector of 15 km is equipped by a Paralleling Station (PS) positioned at the mid-point. A 9 kV power system is added. The feed-wire is supplied by AC/DC converters which are installed in some of the existing substations. SSTs allow increasing the power supplied in the 1.5 kV electrification system. They are connected to the 1.5 kV contact line at the sector mid-points. This makes it possible to take advantage of switches and circuit breakers already installed in the PSs.

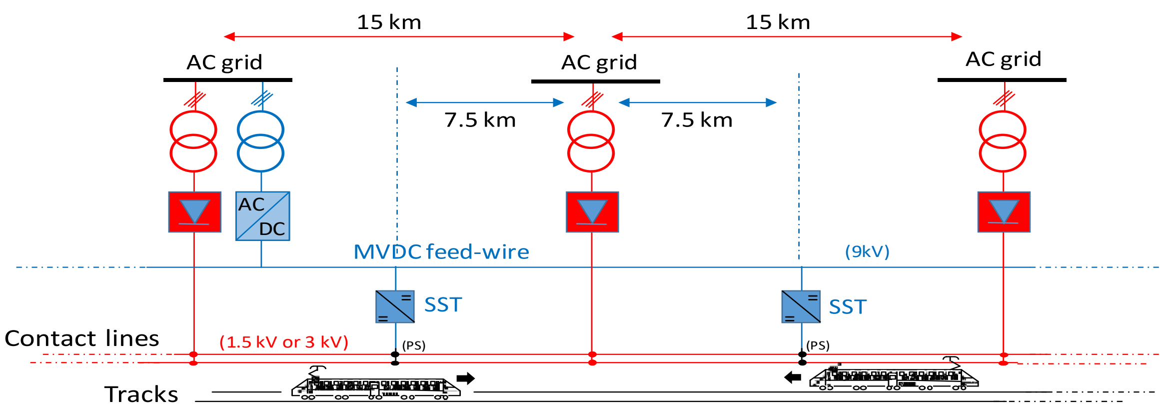

***Fig. 9:** Principle of reinforcement of a DC line by a 9 kV feed-wire.*

In red: existing electrification system; in blue: additional 9 kV power system

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A line with a length of 120 km was considered. As it was mentioned before, this application case, roughly corresponds to the scenario of a French railway line which could be dedicated to freight transport. In the simulations, the trains are running at a constant speed of 120 km/h and the railroad traffic is such that there is a train in each direction every quarter of an hour. That is to say four trains distributed on each track along the 120 km. The simulation results are summarized in Table 1. V_{loc} min is the minimum value of the pantograph voltage for a train running over the 120 km. P_{loc} avg is the average power which can be absorbed by each train considering the locomotive power limitation versus pantograph voltage. The efficiency of the system is calculated considering the total power absorbed by the eight trains and the total losses in contact lines, feed-wires and rails.

Electrification System	V_{loc} min	P_{loc} avg	Efficiency (%)
Initial situation 1.5 kV DC system (S_{cl} = 630 mm^2) (V_0 = 1,75 kV)	1.23 kV	4.8 MW	0.82
Reinforcement : 1.5 kV DC + 9kV DC feed-wire (S_{cl} = 630 mm^2) ; (S_f = 256 mm^2)	1.37 kV	6.1 MW	0.86
Final situation 9 kV DC system (V_0 = 10,5 kV) (S_{cl} = 256 mm^2)	9.07 kV	7.2 MW	0.92

Table 1: *Double track line with a length of 120 km with 4 trains in each direction. Performances versus electrification system*
(Scl: contact line cross-section per track; Sf: additional feed-wire cross-section per track)

In the reinforcement scenario, a limitation of the output current at 4 kA is implemented in the SST control system. This value was chosen to insure a minimum value of the pantograph voltage at 1.3 kV. In conclusion, the reinforcement solution allows to increase by 27% the power of the trains while improving the efficiency of the power system. Nevertheless, it requires the installation on the catenary posts of a new feed-wire with a cross-section of 256 mm^2. Finally, it is interesting also to have a look at the final situation with the 9 kV electrification system. The results are very impressive, compared to the initial situation, the power of trains is increased by 50 % and the efficiency of the power system is 92 %. The contact-line cross-section can be reduced to 256 mm^2. Taking into account the cost of copper, when renewing the contact line, this will save around 5 million euros for 120 km of double-track line.

Characterisation and modelling of an elementary module of the SST

The SST is based on an association of elementary isolated DC/DC converters. According to **Fig. 11**, on 9 kV side, the inputs of the elementary converters are connected in series and on 1.5 kV side, the outputs are connected in parallel. This configuration, with the Input-Series and Output-Paralleled (ISOP) converter, allows natural voltage and current balancing. The efficiency is an essential criterion and it is recommended to have a sufficiently high switching frequency in order to reduce filter elements, noise pollution, volume and mass of the medium frequency transformers (MFTs). In order to meet all these constraints, the concept of soft switching is indispensable.

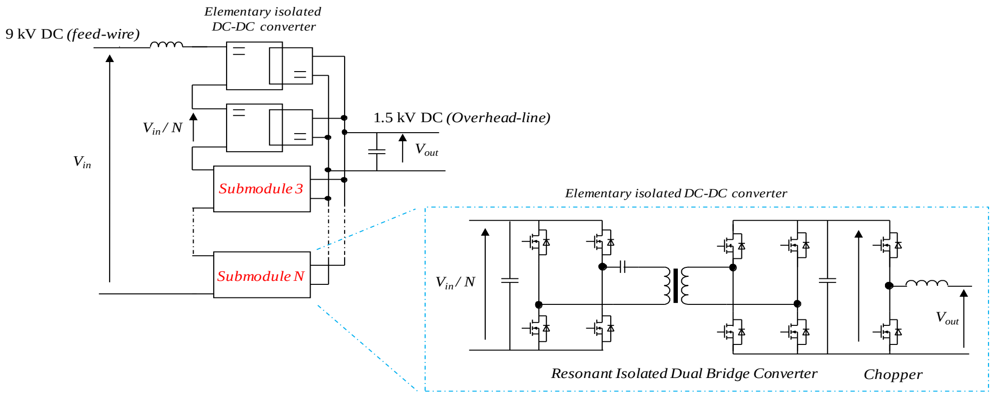

Fig. 11: *Topology of the SST - Association of Isolated DC/DC Converters in ISOP configuration.*

The objective of this work is to provide the losses assessment of the elementary isolated DC/DC converter under output current limitation. The converter has been studied according to several scenarios based on mathematical modelling, PLECS simulations and experimental tests, including different control concepts, topologies and semiconductors devices. Specifically, the resonant dual bridge converter integrates a resonant capacitor in series with the medium frequency transformer. It is able to deliver the highest efficiency compared to other topologies due its capability to provide soft switching operation with quasi-sinusoidal currents. According to the scenario studied in the previous section, the output power must be controlled by limiting the output current. On the Resonant Isolated Dual Bridge Converter (RIDBC), it can be done by frequency control, duty cycle or phase shift controls or using an additional chopper as shown in **Fig. 11**. In one hand, duty cycle or phase shift controls increase turn-off losses during the output current limitation, which affects directly the efficiency. In other hand, the frequency control or the additional output chopper are able to maintain the total switching losses very low. The frequency control on a Resonant Single Active Bridge (RSAB) in discontinuous conduction mode requires less semiconductor devices. In other hands, the output chopper is a well-known and is a more reliable way for controlling the output current, especially in case of short-circuit between the contact line and the rails. Furthermore, this solution is versatile and will be used for interfacing renewable energy sources and storage devices to the 9 kV power system. As a result, the topology associating RSAB, at constant operating frequency, and choppers has been elected to be the most suitable.

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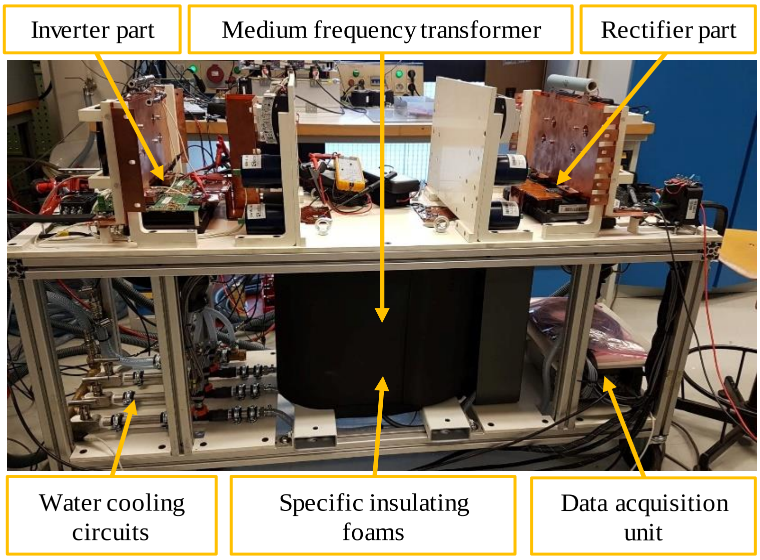


Fig. 12 Resonant Isolated DC/DC converter test bench at Laplace

For experimental tests, a water cooled 300kW RSAB prototype rated to 1.8kV and 170A has been deployed. This setup, presented in **Fig. 12**, has been prepared to work with the opposition method, allowing the characterisation of power semiconductors according to the real working conditions. In addition, it is able to measure the efficiency using two different methods for reliability purposes, computing the losses by the electrical and the calorimetric methods. Such experimental test bench, rated for full power and with accurate efficiency measurements, is fundamental to achieve results far beyond those given by theoretical calculations and simulations.

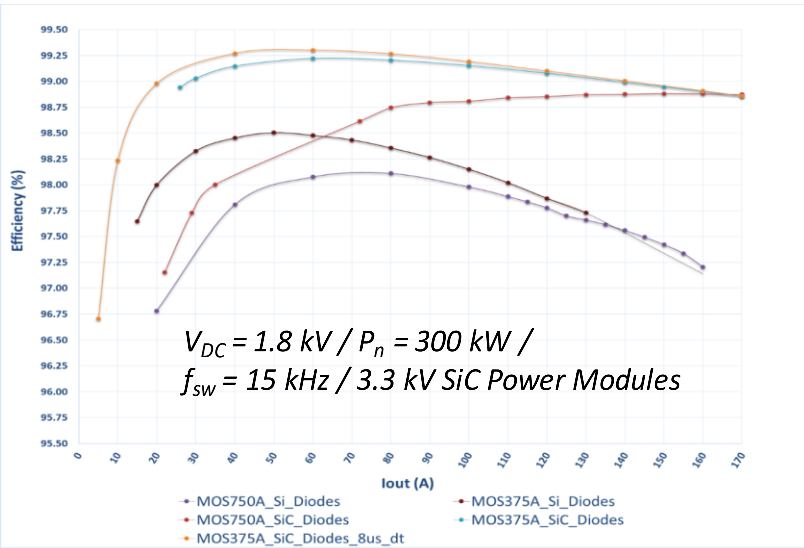


Fig. 13 Resonant Isolated DC/DC converter experimental results Efficiency versus output current.

A first series of tests was carried out with 3.3 kV/750A SiC-MOSFETs and an outstanding average efficiency 98.56% has been obtained. Aiming to obtain further efficiency improvement, based on the influence of the device's parasitic capacitance and on the dead-time, 3.3 kV/375A SiC-MOSFET devices have been tested showing the best average efficiency of 99.10% as shown in **Fig. 13**. These devices are 33% cheaper that the first one and they have been elected to be the most suitable for the application. Overall, the simulations and experimental results carried out in this study are very promising and have demonstrated the short-term feasibility of an industrial solution since 3.3 kV SiC MOSFET modules are now in production and medium-frequency transformer technology is state-of-the-art for traction-transformer manufacturers.

WP5 COMMUNICATION, DISSEMINATION AND LINK WITH OTHER S2R PROJECTS

Task Leader: UIC

Collaboration with Shift2Rail IP3 Project IN2STEMPO

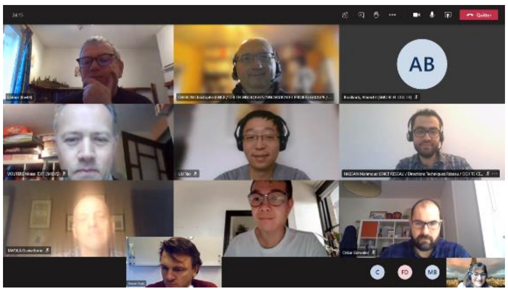
FUNDRES partners are closely collaborating with its complementary project IN2STEMPO.

The IN2STEMPO coordinator, Garry Bosworth from Network Rail, was invited to present the IN2STEMPO project "Innovative Solutions in Future Stations, Energy Metering and Power Supply" at FUNDRES Kick-off meeting on 28 November 2019 at SNCF Réseau in Saint-Denis. Project partners shared their work many times in 2020 and several IN2STEMPO partners are members of the FUNDRES Advisory Board.

The December 2020 edition of IN2STEMPO newsletter is available on IN2STEMPO project website.

FUNDRES held its first Advisory Board online on 1st December 2020

Participants from SNCF IR, SNCF Réseau, CAF, Alstom, Siemens Mobility and ERA joined the project partners online to:



- ✓ examine the project results with the members of the consortium;
- ✓ provide technical, ethical and legal guidance, input and feedback on the requested objectives and technology needs;
- ✓ propose and encourage the potential interactions of the project with other IP3 project initiatives and activities, and;
- ✓ identify the results for dissemination.

The project coordinator presented an overview of the project objectives. All work package leaders then presented the progress and current achievements. Discussions with the advisory board members were animated and they expressed that the results to date seem interesting, sustainability being a key subject.

The project duration is short and therefore cannot cover all topics. However, one output of the project should be to consider the additional investigations to perform after the project, including short circuit breaker. This will allow identify further projects for these "open topics" at the end of FUNDRES, within the next Shift2Rail framework or others.

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Presentation of FUNDRES at the Shift2Rail Innovation Days on 23 October 2020

Philippe Ladoux, coordinator of FUNDRES presented the project in a parallel session of the Shift2Rail Innovation Days that were held remotely on 22-23 October 2020.

The Shift2Rail Innovation Days gave a unique opportunity to hear from high-level panellists about rail's crucial role in the mobility and transport recovery effort, Shift2Rail's successor, the European Year of Rail in 2021, and much more!

On Day 2, FUNDRES was presented in a parallel session called "Cost-efficient, sustainable and reliable high capacity infrastructure". This session was a great moment given to four Shift2Rail IP3 projects, namely ASSETS4RAIL, IN2TRACK2, IN2STEMPO and FUNDRES to present their work and share experience.

The FUNDRES presentation delivered on that occasion can be downloaded HERE.

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