Deliverable 3.2
Digital twin Demonstration

Project acronym:	FUNDRES
Starting date:	01/12/2019
Duration (in months):	24
Call (part) identifier:	H2020-S2R-CFM/OC-IP/CCA-2019-12
Grant agreement no:	881772
Due date of deliverable:	20 Month
Actual submission date:	15-11-2021
Responsible/Author:	Francesco Castelli Dezza/POLIMI
Dissemination level:	PU
Status:	Issued

Reviewed: Yes

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

Document history		
Revision	*Date*	*Description*
1	01/10/2021	First issue

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Contents

List of Abbreviations

ERPS	*Electric Railway Power System*
DT	*Digital Twin*
ESS	*Energy Storage System*
RES	*Renewable Energy Sources*
IoT	*Internet of Things*
EMI	*Electromagnetic Interface*
HIL	*Hardware In Loop*
CPU	*Central Processing Unit*
EV	*Electric Vehicle*
PE	*Power Electronics*
OCS	*Overhead Catenary System*
MPPT	*Maximum Power Point Tracking*
WT	*Wind Turbine*
PV	*Photo Voltaic*
TPSS	*Traction Power Substation*

Chapter 1

Digital Twin Demonstration

1.1 Introduction

Nowadays, in lots of countries ERPS are in attendance and it is on the nationwide future projects of construction. ERPS function is complex and entails dynamics, communication, and signaling, power converter, tracks, etc. for which DT could be a sensible platform for design, testing, and evaluation [1]. Because of the high level of complexity in ERPS, computer-based simulators might not be able to carry out such comprehensive evaluation while DT could be applied so to improve the efficiency and safety of ERPS. Neglecting signaling system in ERPS, the main application of DT in this field can be categorized as Fig. 1.1.

1) Energy management: The ERPS is known as a huge high-power network connected to the grid with time-varying loads (trains). Besides, the integration of renewable energy sources (RES), and energy storage systems (ESS) make the energy control in such a system more complex. Accordingly, the energy management needs the continuous and dynamic coordination of various parts including: braking/motoring trains, traction substation auxiliary loads, ESSs and RES [2]. The communication of different layers in such a network can be implemented by concept of internet of things (IoT) using DT technology.

2) Power flow analysis: Depending on the structure of ERPS type and traditional or reversible traction substation in the line, different power flow methods can be implemented. Meanwhile, auxiliary power flow controllers which are based on power electronics converter are a promising solution to facilitate power flow control in ERPS. Measuring powers in different parts of the network and sending information to aggregator aiming the optimized power flow requires DT concept implementation [3].

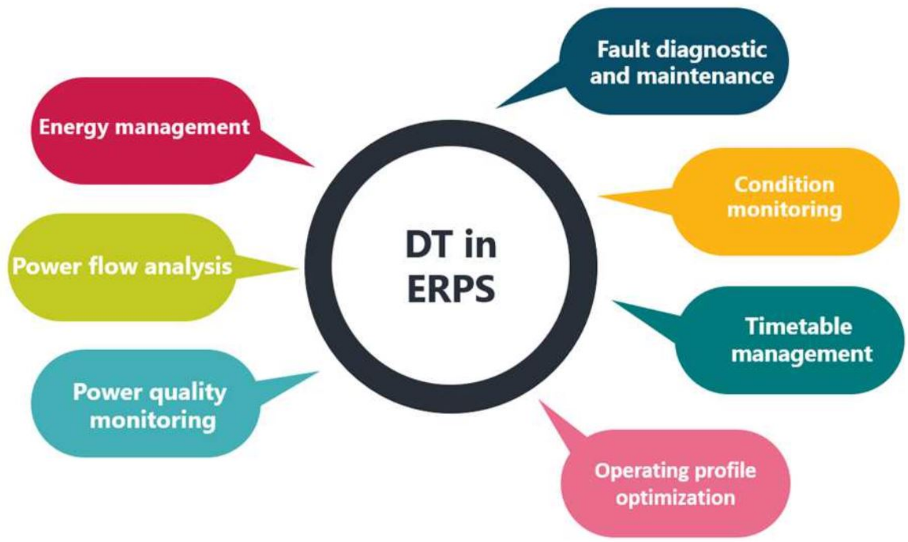

Figure 1.1: Applications of digital twin in electric railway power system.

3) Power quality monitoring: Electrical compatibility between upstream grid and ERPS is critical facing power quality and reliability issues. ERPSs are known as one of the most polluted network from the power quality perspective [4]. Simulation of these issues in software it's not possible due to the limitation of modeling blocks and CPU. Different resonance situations, transient events and EMI are amoung the complex phenomena which may need exact real data measurement to be modeled. This highlights the need for DT implementation.

4) Fault diagnostic and maintenance: Trains and electric multiple units which contain a control part, a power circuit, various sensors, etc. are exposed to the mechanical vibrations and electromagnetic interference. On the other side, traction converters, the power electronic switches and sensors are sensitive to the faults. Motivated by these issues, the analysis of fault diagnosis and maintenance in ERPS has become a critical subject which can alleviate consequently deviations and transients. Even though applying offline simulations can be helpful for analyzing unusual situation in a particular part, but it will be a difficult function to emulate various abnormalities and faults in the whole ERPS. Hence, there is an urgent need to use DT and real-time HIL in this area [28].

5) Condition monitoring: As mentioned before, on time identification of faults in ERPS is critical for the availability, reliability, and safety reasons. To decrease the failure risk in ERPS, it is important to obtain, accumulate, and procedure detailed data regarding the technical condition of equipment. It can provide prediction for any destruction to the electric equipment. Faults diagnosis and maintenance is

the next step after ERPS infrastructure condition monitoring. Among the ERPS equipment which may need condition monitoring it can be mention to the return circuit, track circuit, impedance bond and pantograph-catenary including arcing, overheating and abrasion.

6) Timetable management: The management of trains traffic in ERPS especially in crowded areas commonly is according to the off-line timetable design. Providing such a timetable schedule may need several months to include many variable situations and all possible conflicts among trains. Using the concept of DT and real-time, trains traffic and movements are managed with exact stability to the timetable. It facilitates planning train routes, sequences, and stop/crossing times at stations, with the purpose of regulating the impacted schedules from disturbances and decreasing negative consequences.

7) Operating profile optimization: In ERPSs, the energy efficiency is significantly impressed by the train operating profile including timetables and the applied driving modes. The operating profile optimization concerns the train control issues, for instance, optimizing the order of driving modes including accelerating, cruising, coasting, and braking together with the exchanging points between the modes, aiming of minimizing energy consumption and increasing system efficiency. It requires a dynamic model of the train and real-time measurement of system for energy calculations. This can be executed by concept of internet of things (IoT) using DT technology.

In this project, a DT of future 9 kV DC system is proposed using MATLAB software integrating distributed energy sources and EV charging infrastructures [5]. In the proposed system, an algorithm is modified to accept real-data from physical railway system and simulate DT model based on the real data. The overall architecture of implementing digital twin for 9 kV DC railway line is demonstrated in Fig. 1.2. The used cases studies for modeling and for contribution of digital twin will be divided into 3 categories:

- Low-level based on simplified model to study various elements for long time.
- Mid-level for use case to analyze the impact on the AC mains and on the other elements, e.g. renewable generators and charging infrastructures.
- High level to study transient events and protection strategies.

The modelling of power flows in different scenarios contribute to the digital twin by:

- Giving the performances of the future DC Railway electrification system;
- Allowing to find the sizing power and the overload degree for the various power

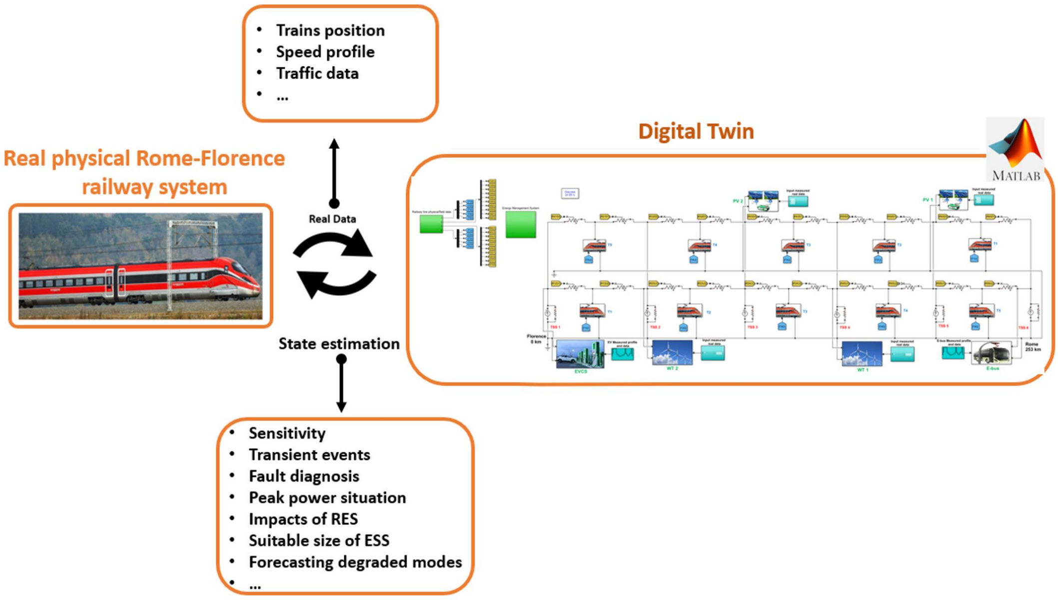

Figure 1.2: General scope and architecture of implementing digital twin for 9 kV DC railway line.

converters, the suitable size of the storage systems in relation to the railway traffic;

- Evaluating the impact of use energy coming from solar panels or wind turbines;

1.2 General scope of Implementing of digital twin for 9 kV DC ERS

To imitate a comprehensive and exact model of ERPS as a DT, the behavior and performance of each of its subdivisions must be analyzed and modeled. The overall architecture of ERPS DT is composed of four main elements as follow:

1.2.1 Digital twin model of proposed smart 9 kV railway system

The main and first part to extract DT of proposed system is architecture of ERPS composed of four main parts as follow:

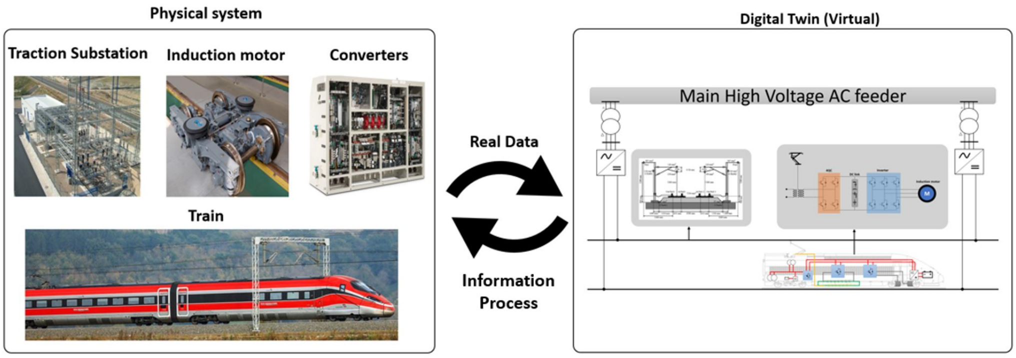

Figure 1.3: DT model of different parts of railway system.

Power Electronic Converter based TPSS Model in DT

Real-time emulating of device-level PE converter models display a critical role in ERPS by providing precision prediction of elements stresses to layout better control and protection methods.

Train Traction Motor's Driving System and it's movement in DT

The DT model for driving of traction motors (for example in modern trains) must considered all subsystems like saturate onboard transformer, four quadrant converters, dc-link and chopper, inverters and induction motors.

Due to the complex multi-wire overhead supplying system in ERPS, the OCS must be modeled precisely to analyze current distribution, and power quality monitoring including EMI, and harmonic and resonance issues. On the other side, by addressing the interaction of a real pantograph with a mathematical model of the OCS, DT and real-time based simulation are capable of identically demonstrating its dynamic behavior.

Multi-train Operating System Data in DT

Multi-train and real traffic based ERPS is complex to analyze and simulation in software due to large size of the system considering optimization of traffic, speed profile, driving strategies, and timetable management and their characteristics. To tackle these complexity, DT emulation can be a promising solution considering, as dynamic nodal methods with variable-size matrices realizing nonlinear ERPS behaviors and an equivalent current sources. The overall architecture of railway system DT with different parts is demonstrated in Fig. 1.3.

In order to extract DT for 9 kV ERPS, the real data of case study line (Rome-

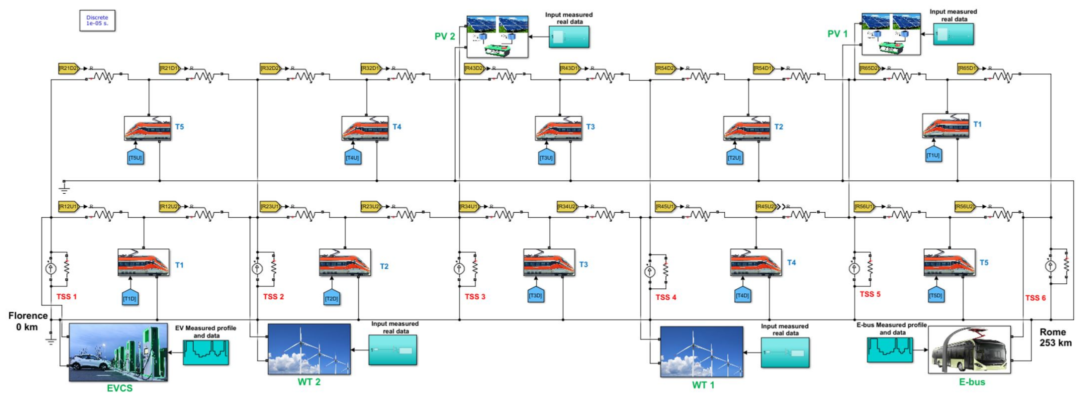

Figure 1.4: Simulink DT model of proposed smart 9 kV railway system.

Florence) as follows are considered as inputs of model. Therefore, the overall architecture is modeled in Simulink as shown in Fig. 1.4.

- **Line data** (distance, altitude, slope, curve radius, maximum speed in each section)
- **Trains data** (Tractive effort diagram, weight, equivalent mass factor, min and max acceleration, train and electric braking factors, auxiliary power)
- **Utilization data** (Headway time, stop time, minimum mechanical braking speed, no-load voltage of substations, minimum allowed voltage, maximum currents of trains)

1.3 General scope of implementing digital twin for PV and ESS

According to the input data of PV plant (annual radiance and temperature maps around case study line of Rome-Florence), DT model of PV is modeled as shown in Fig. 1.5 to be connected in the proposed 9 kV dc system. Here, the two connection points for PV plants are designed based on the annual statistics. Meanwhile, as illustrated in the figure, the controlling system is based on MPPT P&O technique. The input data of PV DT is demonstrated in Fig. 1.6. The model can accept different scenarios (weather conditions) including sunny, cloudy or rainy day data. Fig. 1.7, shows the integrating points and implementation of PV DT in proposed 9 kV DC system. In order to improve the simulation speed to execute for 24 hours, the output of PV DT is implemented as current control system.

It is known that, solar and wind energy are strongly dependent on weather resources

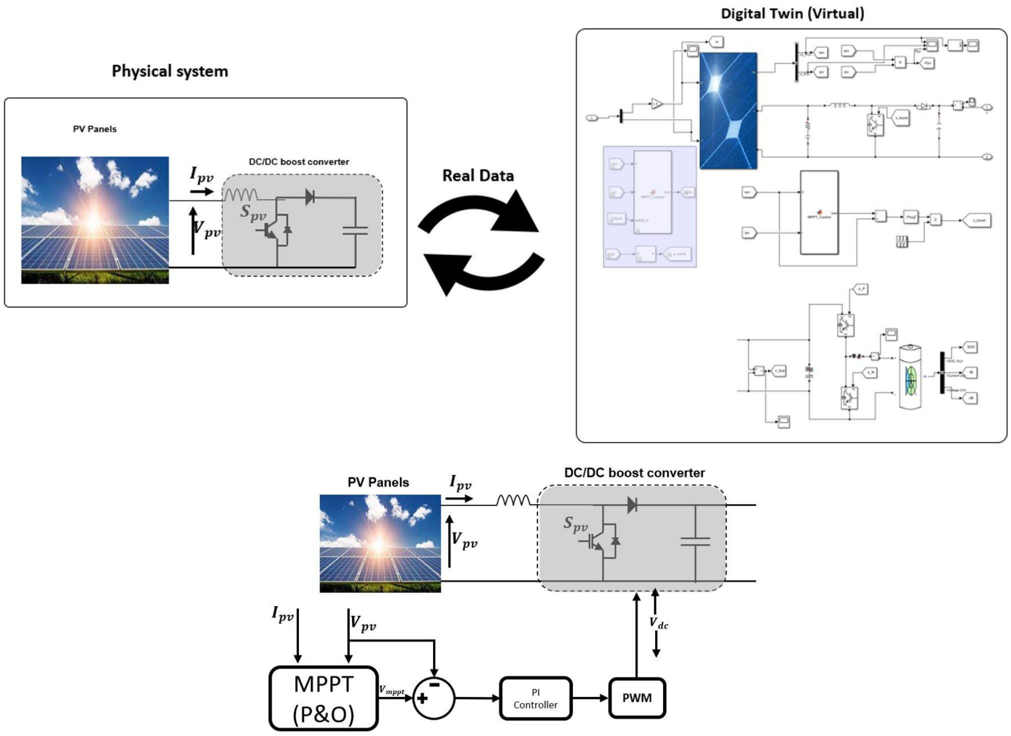

Figure 1.5: Simulink DT model of proposed PV plant system with it's control system.

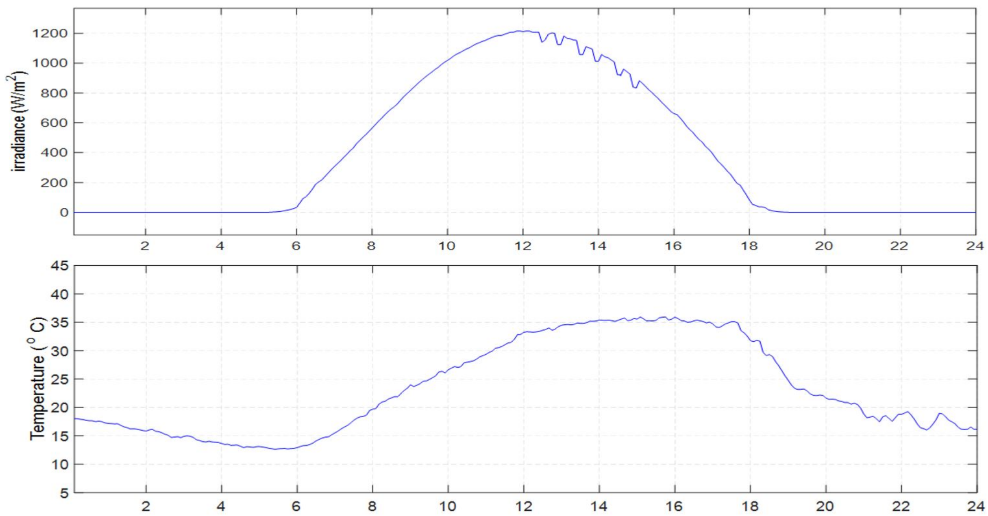

Figure 1.6: Input real data of DT model of proposed PV plant system.

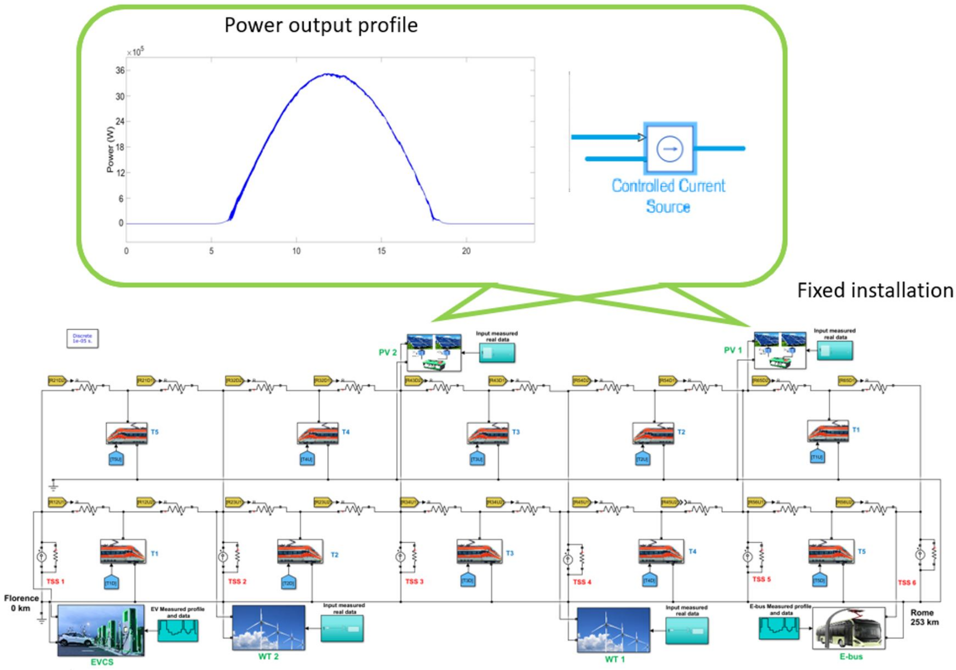

Figure 1.7: Implementing output of DT model of proposed PV plant system in 9 kV DC system.

with intermittent and fluctuating features. To filter these variabilities, battery energy storage systems have been broadly accepted as one of the potential solutions, with advantages such as fast response capability, sustained power delivery and geographical independence. Extracting DT model of storage unit including the required converter and control system to be connected to 9 kV DC is accomplished as shown in Fig. 1.8.

1.4 General scope of implementing digital twin for WT

According to the input data of wind farm (annual wind speed maps around case study line of Rome-Florence), DT model of WT is modeled as shown in Fig. 1.9 to be connected in the proposed 9 kV dc system. Here, the two connection points for wind farms are designed based on the annual statistics. Meanwhile, as illustrated in the figure, the controlling system is based on MPPT technique. The input data of WT DT is demonstrated in Fig. 1.10. The model can accept different scenarios (weather conditions) including windy, breezy, normal or non-windy day data. Fig. 1.11, shows the integrating points and implementation of WT DT in proposed 9 kV

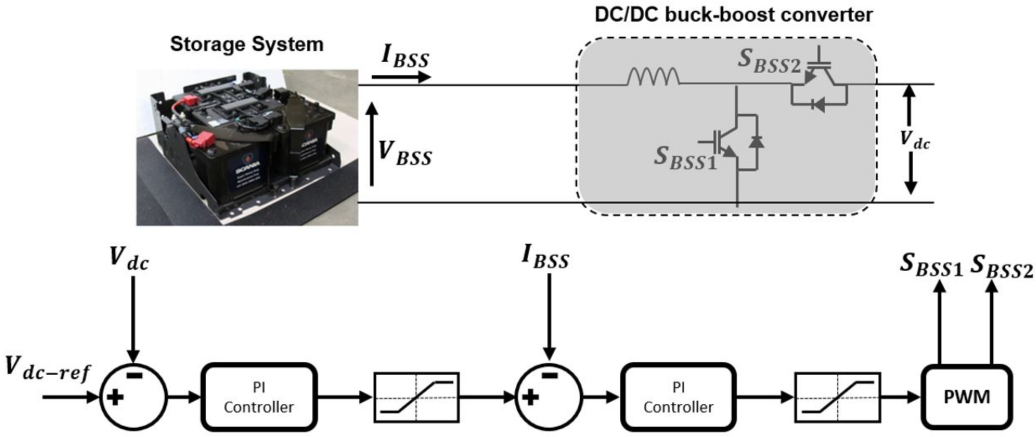

Figure 1.8: Simulink DT model of proposed ESS with it's control system.

DC system. In order to improve the simulation speed to execute for 24 hours, the output of WT DT is implemented as current control system.

1.5 General scope of implementing digital twin for EV charging infrastructures

According to the input real data of EV charging which is based on typical charging profile-arrival and departure time, its DT model emulated as shown in Fig. 1.12 to be connected in the proposed 9 kV dc system. Here, the two connection points for EV charging infrastructures are considered inside beginning and destination cities. Obviously, the urban areas are more critical than other parts, hence, the best sites for interlinking the charging stations with the DC catenary system of the ERPS are train stations, and charging infrastructures can be connected to the ERPS near all the train stations between Rome and Florence. In this project, two charging infrastructures are supposed to be integrated into the ERPS. According to the previous explanation, the train stations at Rome and Florence which are two tourist cities of Italy are selected in order to install the charging infrastructures. The maximum consumed power by these two charging stations is each 500 kW during peak hours. However, the model can accept different scenarios (traffic and charging type conditions). Fig. 1.13, shows the integrating points and implementation of EV charging infrastructures in proposed 9 kV DC system. In order to improve the simulation speed to execute for 24 hours and complete low-level study, the output of EV charging infrastructures DT is implemented as current control system.

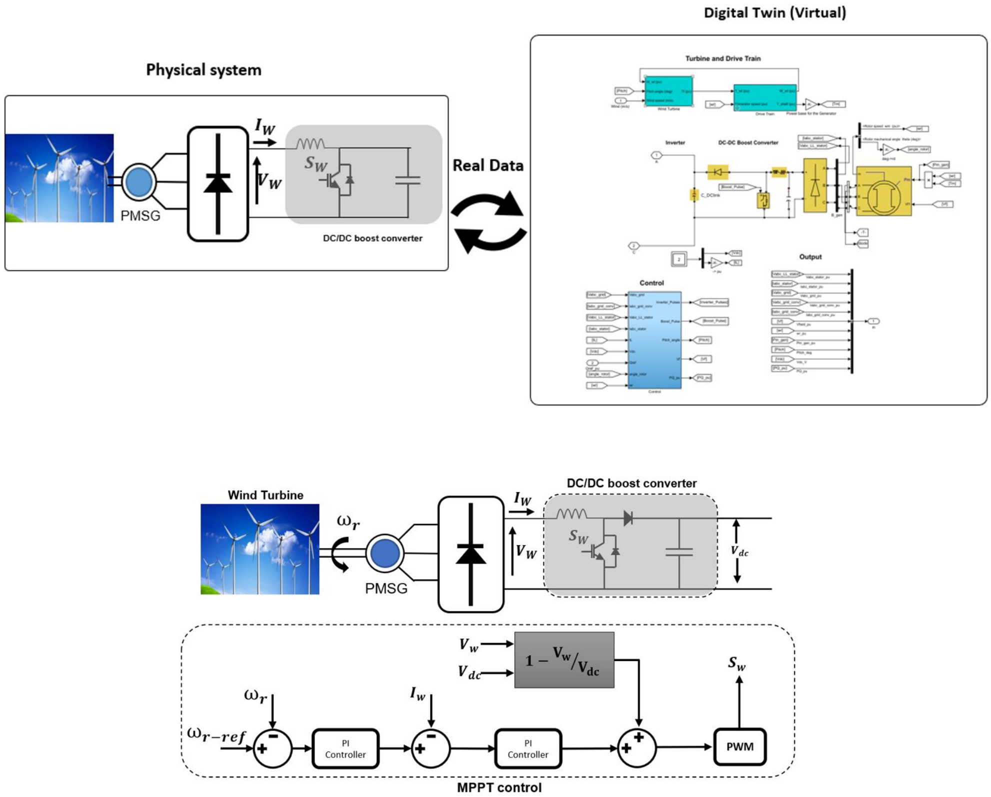

Figure 1.9: Simulink DT model of proposed wind farm system with it's control system.

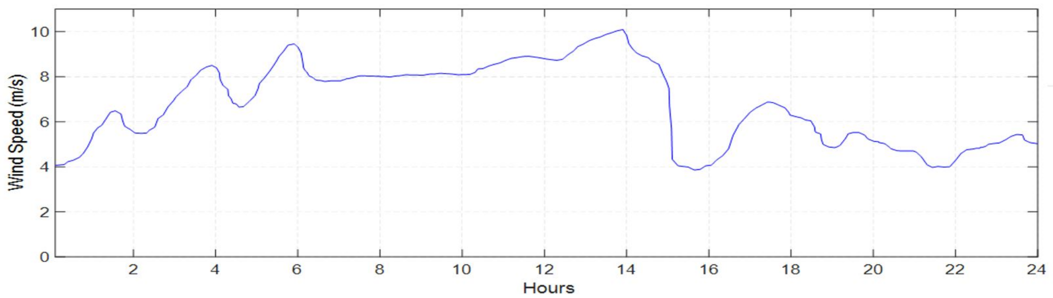

Figure 1.10: Input real data of DT model of proposed wind farm system.

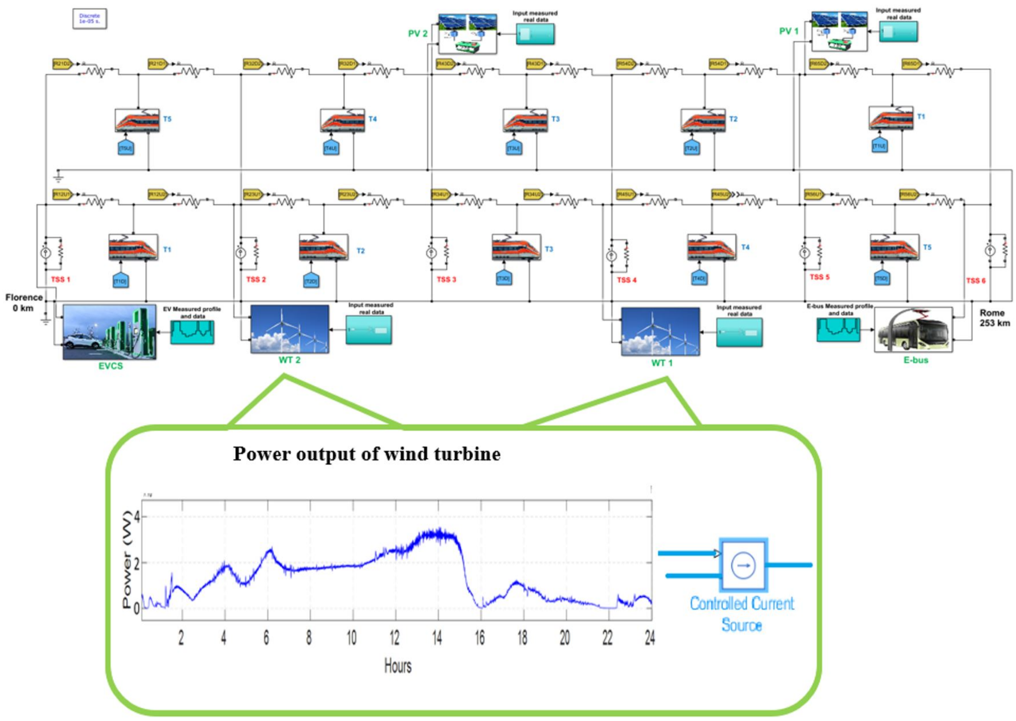

Figure 1.11: Implementing output of DT model of proposed Wind farms in 9 kV DC system.

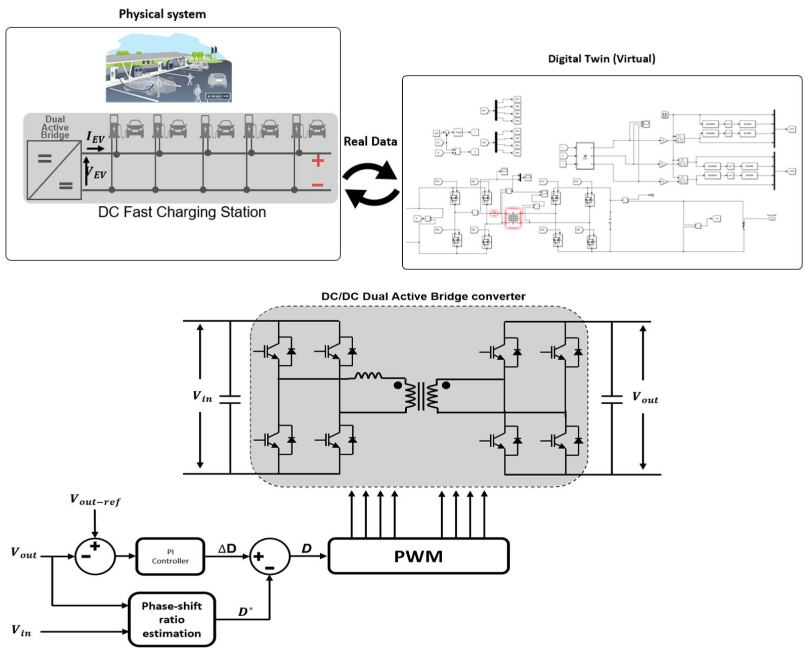

Figure 1.12: Simulink DT model of proposed EV charging infrastructure with it's control system.

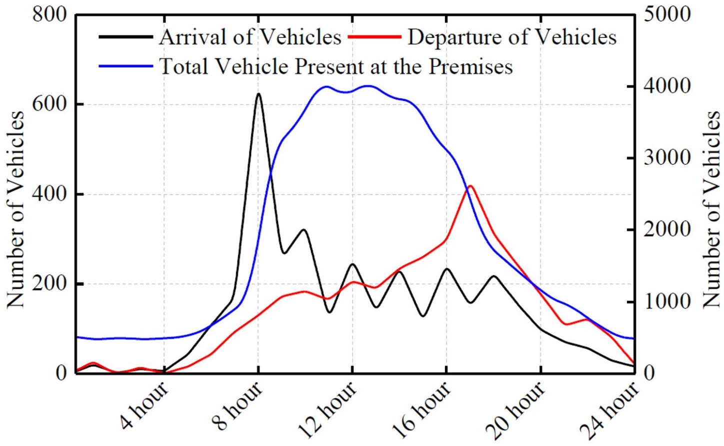

Figure 1.13: Input real data of DT model of proposed EV charging infrastructure system.

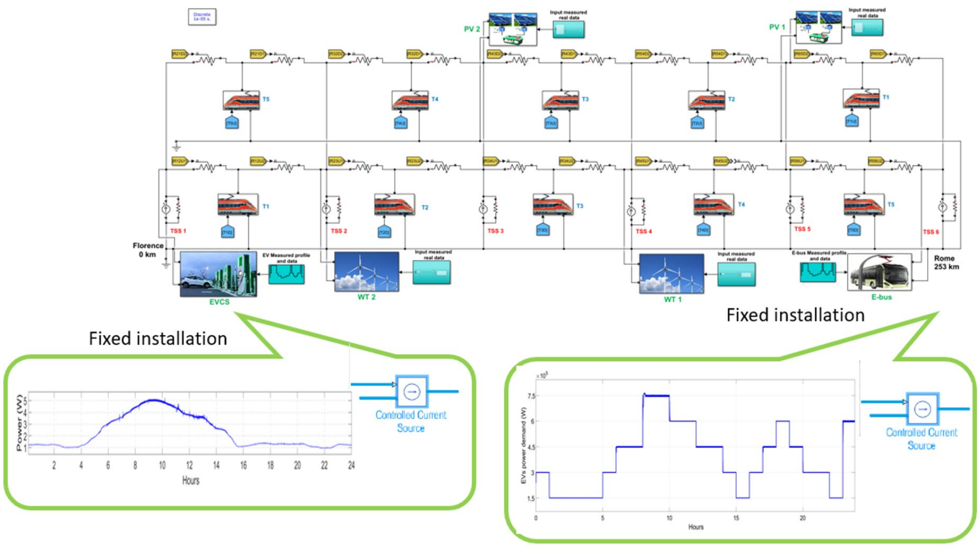

Figure 1.14: Implementing output of DT model of proposed EV charging infrastructure in 9 kV DC system.

1.6 Model Verification

In the following, the input profiles for Digital Twin of electric railway power system at one TPSS is explained. The results which are used for Digital Twin are power outputs of renewable energy sources including PV panels and wind turbines that are presented in Figure 1.15. Also the load profile of electric vehicle is shown in Figure 1.16.

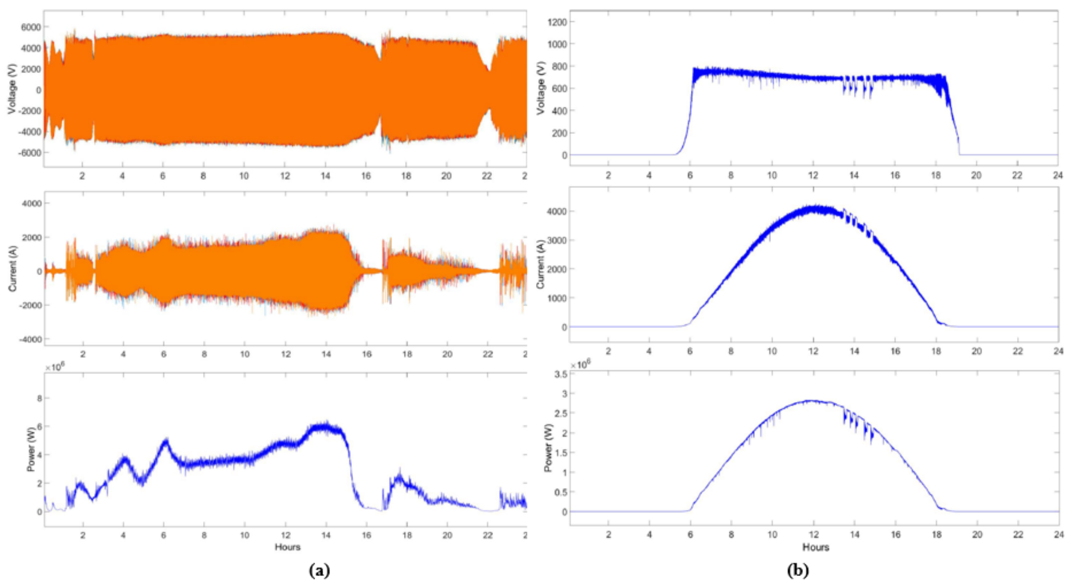

Figure 1.15: Input for digital twin of (a) Wind Turbine; (b) PV panels.

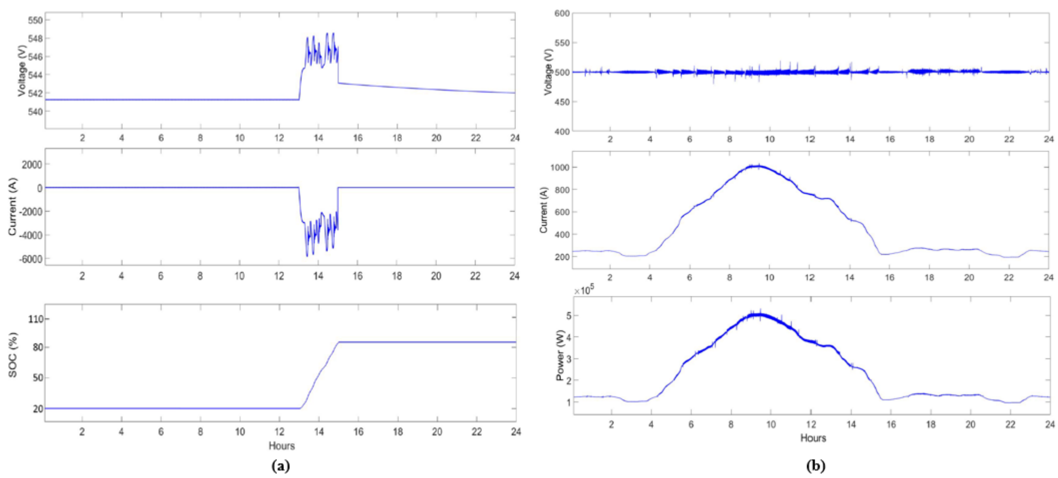

Figure 1.16: Input for digital twin of (a) Storage unit ;(b) charging station.

Figure 1.17 Shows the daily voltage profile of the DC catenary system that remains on 9000 V dc with less than +10% and -10% variation. This is an acceptable range for the voltage profile of the DC catenary system since the voltage changes very fast in the electric railway system and the acceptable range is between +20% and -30% [6].

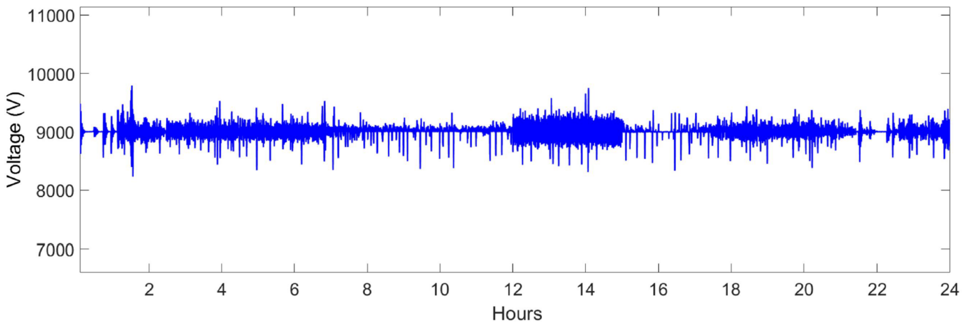

Figure 1.17: Voltage profile of one TPSS.

Figure 1.18 represents the output power of various subsystems including utility grid, fast-charging station, renewable energy sources, and the storage unit. As it can be seen, the system is operative in several working modes defined in power management table. At nights, the ERPS's power demand is at its minimum and both grid and wind generator (if available) are supplying the loads (FM). However, in the mornings, the load's power demand peaks, and thanks to renewable, it can be realized that peak-shaving is happening and drawn power from the grid is much less than the load's power demand (PSM) that is about 30% less. For the rest of the day (around 7.00 a.m. to 8.00 p.m.) the system is mostly working in the feeding mode and the wind/PV/grid system will supply the loads (charging station and trains). In some cases, if the SOC of the storage is 100%, and renewable energy sources generated power exceeds the load's power demand, the extra power will be fed into the main utility grid (RM). The results show that the proposed micro-grid based architecture for ERPS can be a promising solution to reinforce the supply line power and also high traffic issues. In other words, by implementing DESs and integrating with existing ERPSs, it is possible to increase the network power capacity and prevent the establishment of more TPSSs or increase the line voltage.

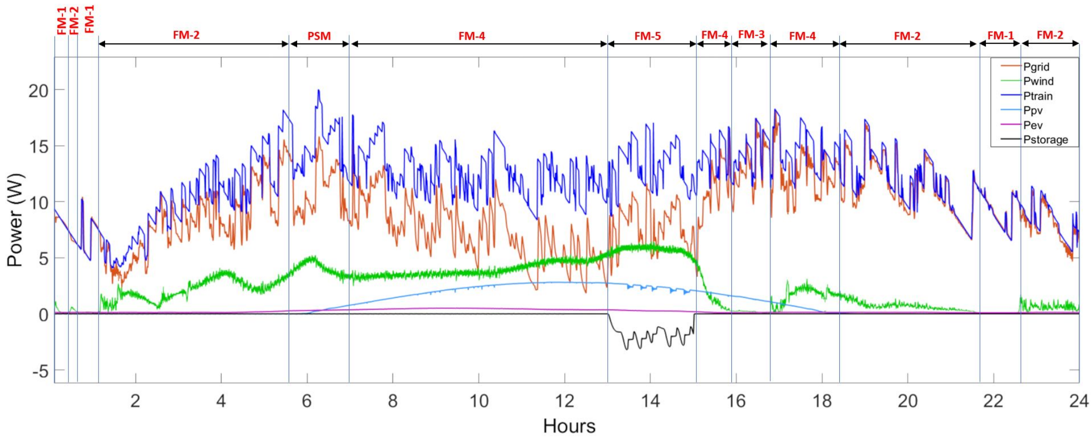

Figure 1.18: Power values for different digital Twin of sources and loads.

In order to demonstrate the outputs of proposed DT and evaluate impacts of RES integration into proposed 9 kV DC hub, the line situation has been modeled in normal working hours using real data as inputs. The measured power of TPSSs are illustrated in Figure 1.19 and Figure 1.20. It is obvious that integrating RES to the line decreases the contracted supplied power by substation. Depending on the weather situation and ratio of RES power to the system power the effect can be enhanced.

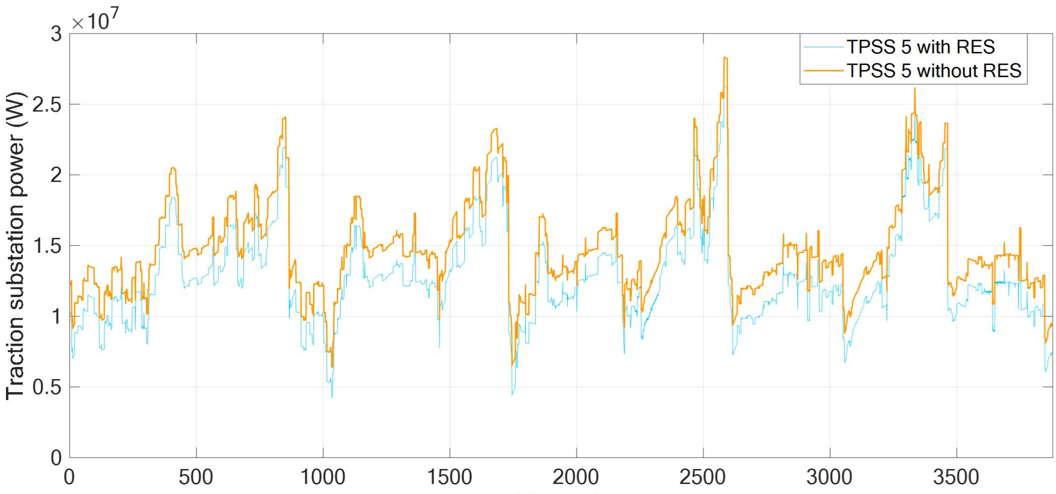

Figure 1.19: TPSS 5 power (close to Rome) with and without integration of RES.

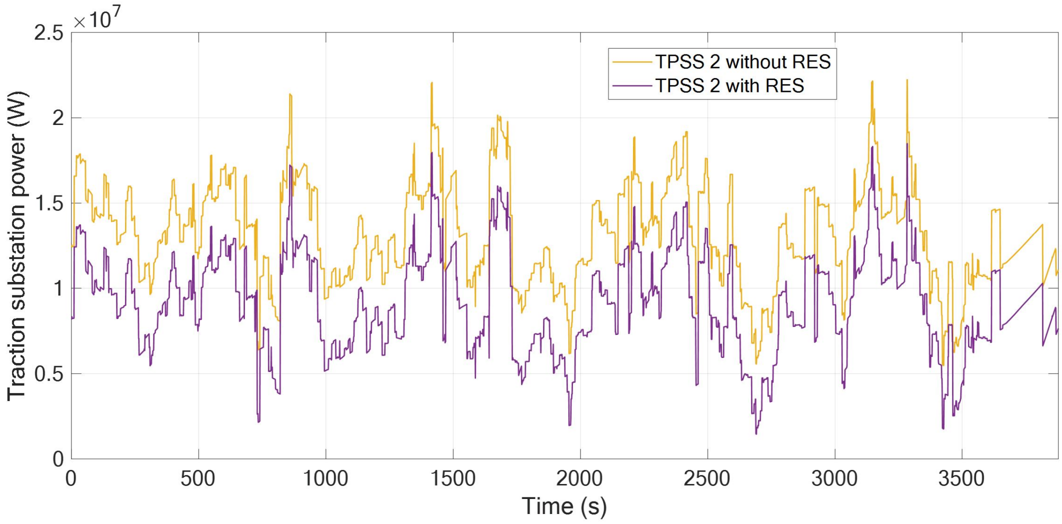

Figure 1.20: TPSS 2 power (close to Florence) with and without integration of RES.

In the other side, the extra power injected by RES can mitigate voltage drop. The output overhead catenary voltage of DT for a section of whole line is illustrated on Figure 1.21.

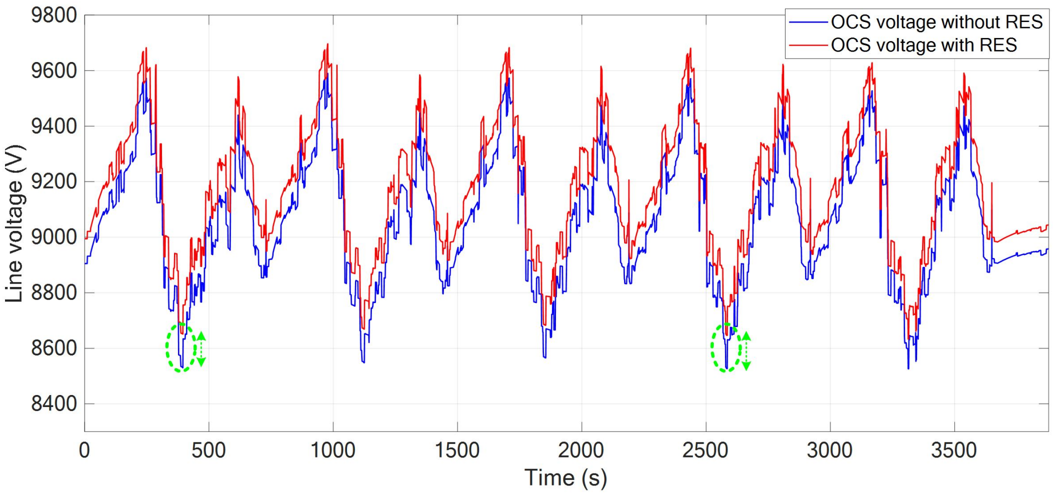

Figure 1.21: Overhead catenary system voltage measured in pantograph point (50-101 km).

The other parameter which has been extracted from the model, is the amount of regenerative braking energy (RBE) in the stop station. The measured power in TSS6 (Rome) is shown in Figure 1.22. Based on the figure, it is obvious that for each train stop the negative power generated by braking can reach 8 MW. If motoring mode trains exist close to the braking section some of RBE can be consumed by them. The difference between blue and green wave-forms (highlighted area) in Figure 1.22 reveals this. However the extra RBE can either be stored by ESS or it can be returned to the network through bidirectional MMC based AC/DC substations. The power profile of TPSS 6 with using ESSs to absorb RBE is shown in Figure 1.23.

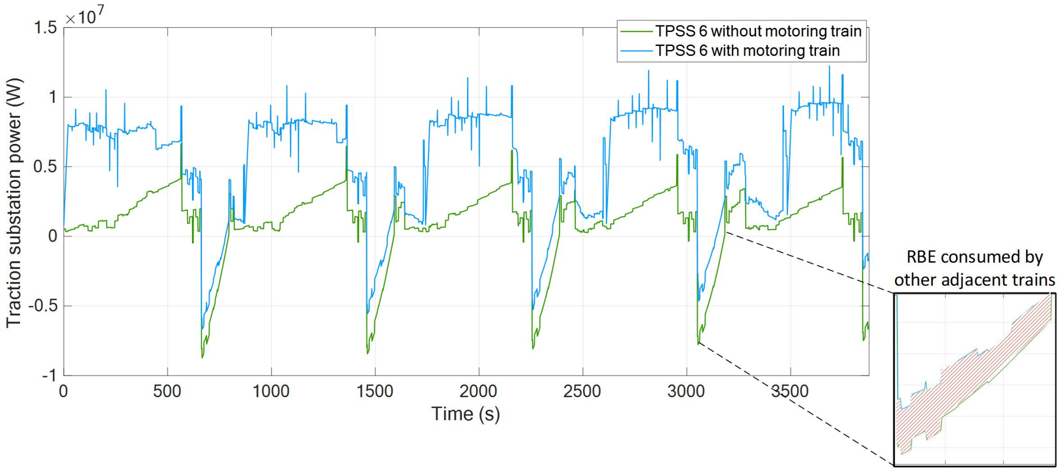

Figure 1.22: TPSS 6 power profile with considering adjacent train and without any consuming trains.

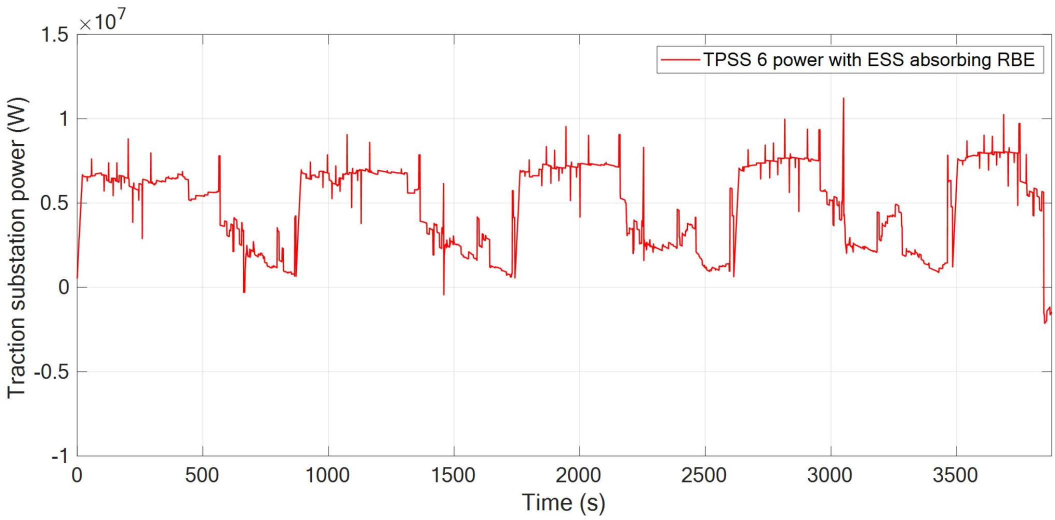

Figure 1.23: TPSS 6 power profile in case of using ESSs to absorb RBE.

1.7 Conclusion

Electric Railway as a high-power load system in power grids known as a key technology in transportation industry. Due to the complexity and breadth of such networks, executing an exact simulation as an integral part of this technology plays a crucial role to obtain reliable and secure operations based on the performance of real physical system. In this context, implementation of Digital Twin (DT) can ensure the correct operation of monitoring and control function. In this project, an approach is presented to implement DT concept both at equipment and system level for future 9 kV MVDC systems integrating RES. It has been shown that DT capabilities to describe the actual and probable future state-run, makes it an unavoidable resolution for ERPS.

The development of digital twin technology in electric railway power systems evaluated considering different sections of electric multiple unit, catenary, traction power substation and multi-train optimization. Utilizing DT modeling, the amount of generated energy by RES absorbed in trains, power flow analysis with and without regenerative braking energy, Power, voltage and current profile of substations, analysis of voltage drops with and without RES across the line and some other measurements related to the sensitivity analysis and transient events can be reached.

The results showed that, the high level of complexity in ERPS, which may cause simulators not to be able to carry out such comprehensive evaluation could be addressed by DT. Since the implementation of the digital twin concept in ERPS as a future trend can be a promising technology to overcome limitations and complexities.

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