EXECUTIVE SUMMARY OF THE THESIS

Towards DC smart grid: integration of renewable energy sources, energy storages, and electric vehicle charging stations into DC railway power systems.

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

The scenario Net Zero by 2050 [1] relies on several decarbonization levers such as electrification of people mobility and improved efficiency of existing energy systems often requiring huge investments. There are also areas of increased efficiency that may contribute to reach the same target but do not necessarily imply significant economic efforts. This thesis addresses one of them: railway and smart mobility have been developed independently at different times and today for the sake of the same efficiency targets can probably find an optimal configuration if integrated.

This paper analyzes and models the Cadorna – Saronno railway line and specifically its sector delimited by the two electrical substations located in Novate and in Saronno, because characterized by intense train traffic with stations already organized with car parks to host a considerable number of cars of daily commuters.

As the first part of this work, the Novate-Saronno sector is modelled to assess how the railway network behaves and if the applicable structural and safety constraints are respected as well as whether there is room to expand the network with new infrastructures so to withstand additional loads represented by electric car parks, battery storage systems and photovoltaic modules.

2. Italian railway system

As any other electrical rail transportation system, the Italian railway network is organized as depicted in the following figure.

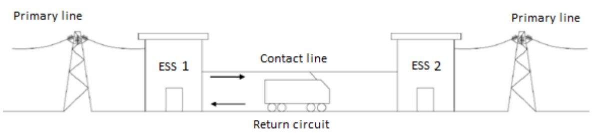


Figure 2.1 Railway network

The track considered has been assumed to have two different sections for the catenary system: FF4 = 610 mm² and FF3 = 460 mm², the first for the two (round trip) tracks which make more stops and the second two for the tracks with less stops. The return circuit has instead a section of 7680 mm².

There are limits in voltage and current for all its components [3] [4]. As far as the electrical substations are concerned these are:

Nominal power [kW]	Nominal current [A]	Mean square current [A]		Peak current [A] (5 min)
		Normal op.	Abnormal op.	
5400	1500	2250	3000	3500

Table 2.1 Electrical substation

Line voltage shall remain within 3600V and 2000V (corresponding to a +20%/-33% range of the nominal voltage) and the catenary system maximum current density shall not exceed 5A/mm² for long periods of time.

3. Methodology

The various components that will compose the DC smartgrid [2], are added one by one to the baseline network model (model of the current railway network) and then subject to dedicated simulations. These components are: car parks, storage systems and photovoltaic modules.

3.1 Train

The trains have been modelled using SIMULINK. The trains running in the considered sector are the TSR EB711/710 having the following characteristic:

TRAIN	TSR EB711/EB710
Rated supply voltage	3 kV
Maximum speed	140 km/h
Continuous power	680 kW
Mass without load	58 t/53 t
Mass at full load	71 t/68 t
Average mass	62.5 t
Maximum acceleration	0.9 m/s²
Maximum deceleration	1.1 m/s²
Base speed [BASE]	40 km/h

Table 3.1 Train parameters

and the following mechanical characteristic curve:

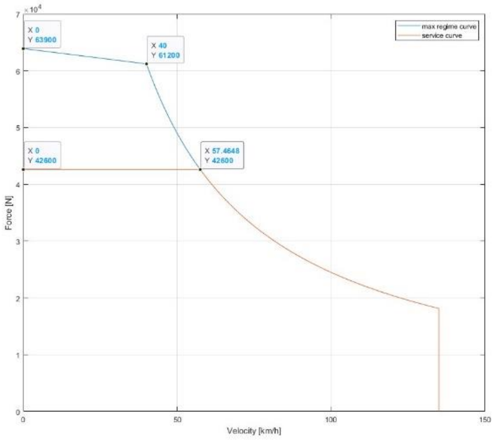


Figure 3.1 Mechanical characteristic

The full mechanical train model is represented in the following figure:

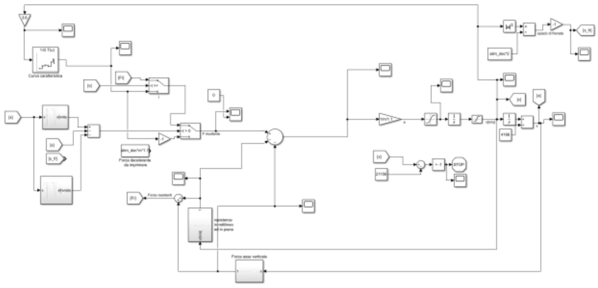


Figure 3.2 SIMULINK train model

The purpose of this train model is to simulate trains position and adsorbed or discharged power at all times.

3.2 Train timetable

The whole actual train timetable have been input but the analysis has been focused splitting the day in two:

- Rush hours, 7.00 to 9.30 and 17.00 to 19.30;
- Off-peak hours, the rest of the day.

3.3 Electric network

The electric network has been modelled according two different configurations. A first one considers the passage of current only through the catenary system, while the second one considers also the return circuit through the tracks and the current dispersed in the ground.

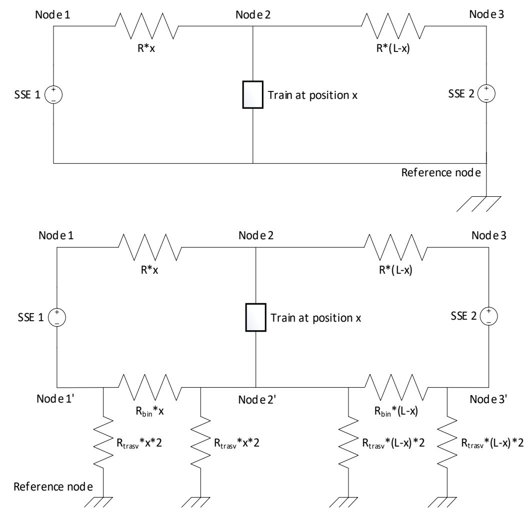


Figure 3.3 Network single track topology

Electric resistances have been calculated as per the following formula:

$$R_{line} = \frac{\rho_{line}}{A_{line}} * x_{posix}$$

Where ρ_{line} is the electrical resistivity:

0.017 $\frac{\Omega\,mm^2}{m}$ (copper) for the contact lines

0.13 (mild iron) for the rails. $x_{posix}$is the distance in meters between two nodes

The ground resistance has a value of 0.5 ohms/km.

3.4 Conductance matrix

Once the resistances are obtained, voltages and/or currents are obtained thanks to the following relation:

$$[\bar{I}] = [\bar{G}] \cdot [\bar{V}]$$

Where:

- $[\bar{I}]$ is the column vector of external nodal current injections;
- $[\bar{G}]$ is the nodal conductance matrix;
- $[\bar{V}]$ is the column vector of nodal voltages.

[G] is defined by the *Graph Inspection method:*
The diagonal terms, G_{ii} are the self-conductance terms, equal to the sum of the conductances of all branches incident to node i

$$G_{ii} = \sum_{(i.k)\in\beta_i} g_{ik}$$

Where:

- β_i is the set of branches connected to node i;
- g_{ik} is the conductance of the branch connecting node i to node k.

The off-diagonal terms, G_{ij} are equal to the negative of the sum of the conductances of the branches directly connecting the two nodes i and j

$$G_{ij} = -g_{ij}$$

3.5 Power flow

On the basis of the power input/output determined by SIMULINK, knowing that:

$$P_{Ti} = (V_i - V_j) \cdot I_{ij}$$

the line/track voltages and the train current are determined through an iterative method:

<u>Step 0:</u> Determine the $[G]$ matrix and factorize it using optimally-ordered sparse LU matrix decomposition. Initialize all catenary node voltages to Vs, all track node voltages to zero, and set the iteration counter k = 0.

<u>Step 1:</u> Increment k by 1 and compute the current injection vector $[I^{(k)}]$ at step k using:

$$I_i^{(k)} = -I_j^{(k)} = \frac{P_{Ti}}{V_i^{(k-1)} - V_j^{(k-1)}}$$

<u>Step 2:</u> Evaluate $[V^{(k)}]$ in the matrix equation using forward-backward substitution.

<u>Step 3:</u> Tolerance check evaluating the power obtained with the new values of V and I with the power given by the mechanical model

$$\left| (V_i^{(k)} - V_j^{(k)}) \cdot I_i^{(k)} - P_{Ti} \right| \le \epsilon$$

if the convergence test is satisfied, stop and this is the solution, otherwise go to Step 1 and repeat.

The simulation duly considers that the two electrical substations are a diode converter and reversibility is not permitted: current can only enter the network.

3.6 Electric car parking

A parking space for electric cars in every railway station along the Novate-Saronno line (with the exception of the smallest one "Garbagnate Parco delle Groane") has been modelled.

14 real charging curves of different sizes (3.7, 10, 20, 100 kW) were analyzed to obtain one "standardized" curves.

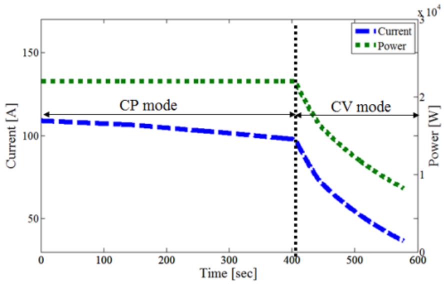


Figure 3.4 Shape of a charging curve

Number of parking slots at each station are:

Stop	Parking spaces	Charger size	Number of chargers	Total energy
Novate	150	20 kW	13	1250 kWh
		100 kW	1	
		3.7 kW	6	
Bollate Centro	80	20 kW	9	670 kWh
		100 kW	0	
		3.7 kW	5	
Bollate Nord	100	20 kW	11	840 kWh
		100 kW	0	
		3.7 kW	5	
Garbagnate Mil.	60	20 kW	6	500 kWh
		100 kW	0	
		3.7 kW	6	
Cesate	150	20 kW	12	1250 kWh
		100 kW	1	
		3.7 kW	7	
Caronno Pertusella	120	20 kW	11	1000 kWh
		100 kW	0	
		3.7 kW	6	
Saronno Sud	50	20 kW	5	420 kWh
		100 kW	0	
		3.7 kW	5	
Saronno	100	20 kW	11	840 kWh
		100 kW	0	
		3.7 kW	5	

Table 3.2 Car parking parameters

3.7 Stationary batteries

Stationary ground storage systems in each station have also been modelled. Each stationary storage management system is a two-input Fuzzy logic which, as output, gives the in/out power.
Input of this logic are the voltage and the state of charge of the batteries at each station.

The resulting fuzzy surface is represented below:

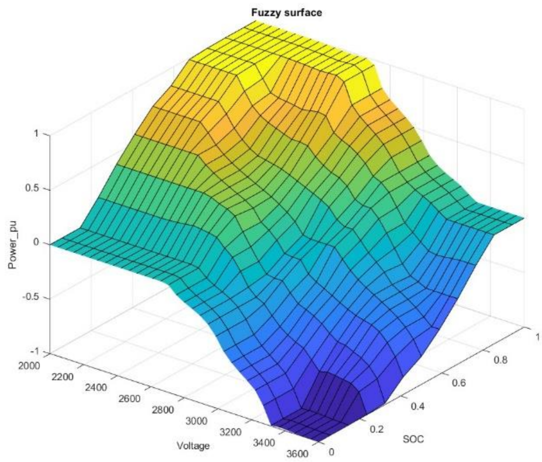


Figure 3.5 Fuzzy surface

3.8 Photovoltaic system

To introduce photovoltaic modules into the model, reference has been made to the meteorological conditions measured in the weather station of the BL25 building of the Politecnico di Milano to determine the irradiation and temperature values. The modelled modules are horizontal thanks to the large existing spaces of the parking slots.
The photovoltaic modules used are the S18K250 of AREO SOLAR and their power output has been determined with the gamma coefficient method.

4. Simulations

Among the different simulation runs the Rush hours are obviously the more stressed in terms of Voltage, current and loads. This summary reports the simulation results during both Rush hours (from 7.30 to 8.30 in the morning) and Off-peak hours (12.30 to 13.30).

4.1 Railway network

A railway network baseline has been set determining voltage and current of lines and substations of the current configuration. These during Rush hours are represented in the following figures 4.1 to 4.3:

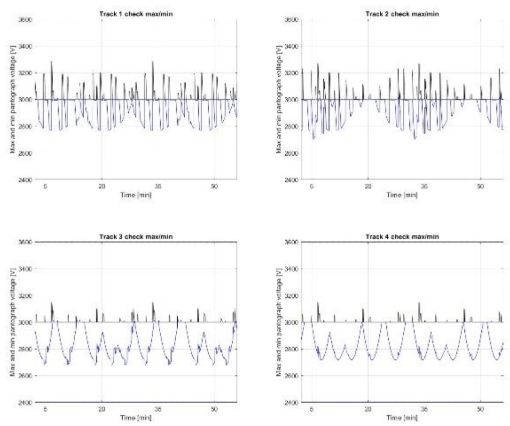


Figure 4.1 Tracks maximum and minimum voltage

	Track Maximum Voltage	Track Minimum Voltage
Rush	3289 V	2680 V
Off-peak	3185 V	2810 V

Table 4.1 Tracks maximum and minimum voltage

These graphs show the maximum and minimum voltage of each track at each time analyzed. voltages are far from the limits (3600 v and 2000 V). In terms of currents during Rush hours:

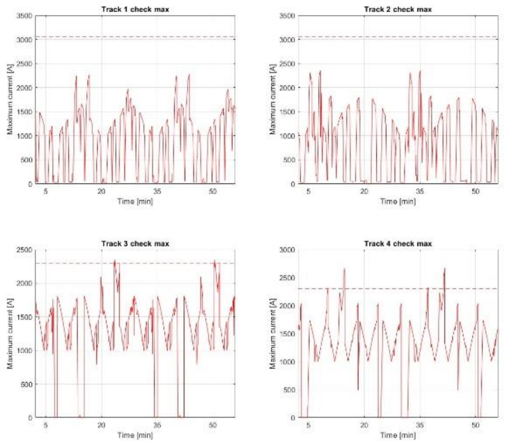


Figure 4.2 Tracks maximum current

With the red dotted line representing the 5A/mm^2. As far as the two electrical substations are concerned during Rush hours:

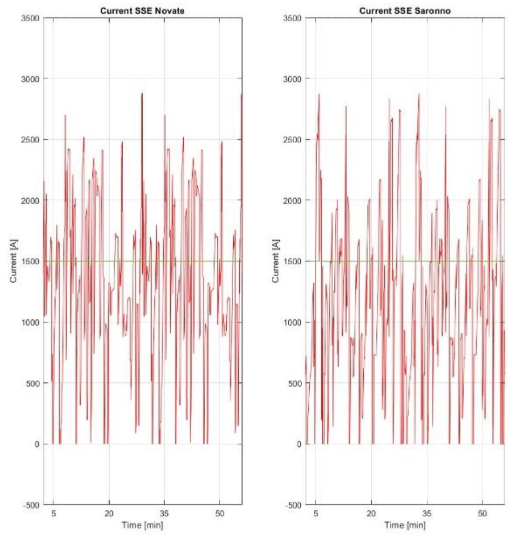


Figure 4.3 ESS's quadratic mean current

The green line represents the nominal current, always well below the limit of 3500 A. Limits are are satisfied also for the quadratic mean current:

	Quadratic mean current ESS Novate	Quadratic mean current ESS Saronno
Rush	1499 A	1373 A
Off-peak	914 A	836 A

Table 4.2 ESS's quadratic mean current

These values are below the limit of 2250 A by far.

The unrecovered energy has also been calculated and it amounts to 34.8 MJ during Rush hours and 22.4 MJ during Off-peak hours for only 16 seconds per each hour as this is a very busy network.

4.2 Car parking

The grid is more stressed with the introduction of the car parks. During a Rush hour:

Track Maximum Voltage	Track Minimum Voltage
3281 V	2670 V

Table 4.3 Tracks maximum and minimum voltage

Quadratic mean current ESS Novate	Quadratic mean current ESS Saronno
1630 A	1471 A

Table 4.4 ESS's quadratic mean current

The max and min voltages differ from baseline (the network in its current configuration) by only about 10 V but the two electrical substations have loaded by additional 100 A approximately.
The unrecovered energy has lowered to 20.2 MJ.

4.3 Battery system

The battery park has been sized as follows:
Nominal Power = 2.72MW representing 50% of power of trains running at Rush hours.
Nominal Energy = 200MJ representing 100% of the energy generated by a brake of train running at Rush hours.
Resulting voltage and current of lines and substations are the following:

Track Maximum Voltage	Track Minimum Voltage
3260 V	2684 V

Table 4.5 Tracks maximum and minimum voltage

Quadratic mean current ESS Novate	Quadratic mean current ESS Saronno
1617 A	1450 A

Table 4.6 ESS's quadratic mean current

Which are lower than the car park case.
The trend of the battery pack with the wider SOC range is:

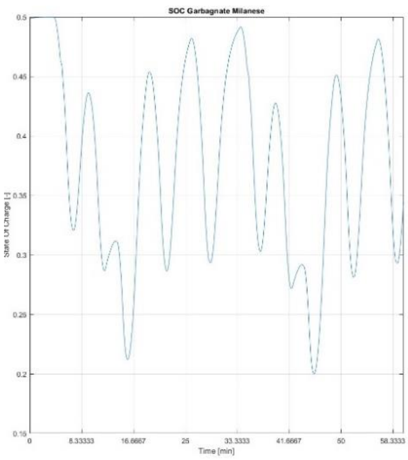


Figure 4.4 State of charge

The unrecovered energy has lowered to 16,5 MJ.

4.4 PV system

When a PV system is added to the network, resulting voltage and current of lines and substations never change significantly throughout the simulated year (2022). Focusing on the most severe day of the year for the PV system (from 12.30 to 13.30 of June 19, 2022) voltage and current of lines become:

	Maximum Voltage	Minimum Voltage
Batteries/PV Off-peak	3180 V	2818 V
Baseline Rush	3289 V	2680 V
Baseline Off-peak	3185 V	2810 V

Table 4.7 Tracks maximum and minimum voltage

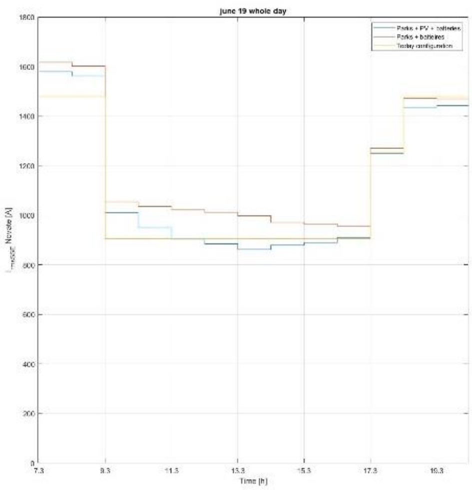
	Currents in Quadratic Mean Novate	Currents in Quadratic Mean Saronno
Batteries/PV Off-peak	886 A	807 A
Baseline Rush	1499 A	1373 A
Baseline Off-peak	914 A	836 A

Table 4.8 ESS's quadratic mean current

The system behaves better than the Baseline case.

The energy unrecovered amounts to 8.6 MJ, compared to 22.4 of the Baseline with Off-peak.

In conclusion, the trend of the two electrical substations throughout the day of June 19 2022 is:



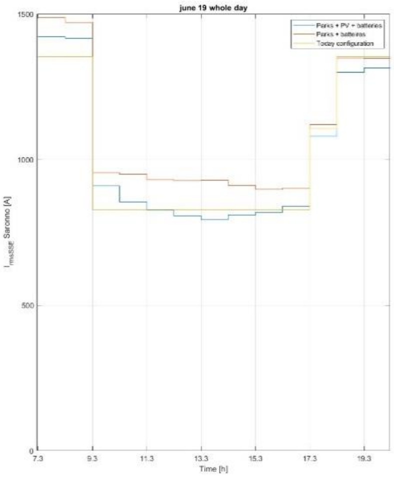


Figure 4.5 Novate and Saronno ESS's quadratic mean currents in the whole day

These figures represent the quadratic mean currents of the: baseline network, Case 2 and case 3, throughout the whole day.

5. Conclusion

This work demonstrates that there is room for exploiting the existing railway network between Novate and Saronno - by adding electric car parks, battery storage systems and photovoltaic modules at the railway stations - allowing to recover energy that is otherwise lost (regenerative recovery of braking trains) as well as better stabilize the railway network voltage.

References

[1] «Trasporti sicuri e sostenibili | Unione europea», *Unione Europea*, 2021. https://european-union.europa.eu/priorities-and-actions/actions-topic/transport_it.

[2] M. Brenna, F. Foiadelli, e D. Zaninelli, «The Compatibility between DC and AC supply of the Italian railway system», in *2011 IEEE Power and Energy Society General Meeting*, San Diego, CA, lug. 2011, pp. 1–7. doi: 10.1109/PES.2011.6039536.

[3] EN 50163, «Railway applications — Supply voltages of traction systems». BRITISH STANDARD, 2020.

[4] EN 50388, «Railway Applications — Fixed installations and rolling stock — Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability». BRITISH STANDARD, 2020.