Railway Infrastructure Simulation Software Test and Validation

by

Daniel del Rivero Peña

Submitted to the Department of Electrical Engineering, Electronics,
Computers and Systems
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Abstract

In this master thesis, the different railway systems and their infrastructure have been studied, in order to provide context for the main topic of this project. This is the validation of the RailNeos 2.0 tool, which was developed by CAF Turnkey & Engineering in association with the University of Oviedo, and funded by ESTEFI project. The validation is based in the comparison between RailNeos 2.0 and its first version of the results from a real railway infrastructure. Once this is done, the same grid will be simulated and analysed in order to explain how a railway system works in a simple manner. At the same time, several modifications will be carried out in the grid to see how their parameters and the energy they manage change.

Index Terms— ESTEFI, RailNeos 2.0, Railway Network Analysis, Railway Systems, Simulation, Validation.

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After six years of hard work as student from the University of Oviedo, today, by finishing this master thesis, I close one of the most important chapters of my life as student, thus leaping towards the professional world.

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Chapter 1

Introduction

1.1 Thesis motivation

There is a need for improving the public transport in urban areas, because of mainly two reasons. The first one, due to the high amount of pollution in urban centres which start to be an enormous healthy problem. According to the World Health Organization (WHO), for each person who dies in a traffic accident, other three lose their life as result of vehicles pollution. The second reason is the current tendency to have a more extensive and less dense urban centres, motivated by new urban policies and the people migration to big cities.

European Union (EU) and their member countries are aware of these facts, promoting their improvements through several politics (giving rise to the project in which this master thesis is framed) such as Roadmap to a single European transport area (2011), the 2006/32/CE, or the 'Plan de ahorro y eficiencia energética 2011-2020' (published by IDAE[1] - 2011) only for mentioning a few.

Furthermore, organizations such as European Association for Storage of Energy (EASE) and European Energy Research Association (EERA) suggest [1] that 'the investment in smart-grids is a key factor for a decarbonized electrical system, increasing share of renewable sources, with more distributed generation and allowing the electrification of the transport sector'. They also indicate that the electrochemical energy

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[1] Instituto para la Diversificación y Ahorro de la Energía - Spain.

storage systems will be a key technology for the transition from centralized energy generation to the distributed energy generation, allowing a massive penetration of renewable energy sources, as well as their smart management (by means of micro-grids and with a more integrated end user in the electric market).

All of these national and European strategical plans reveal the need to research and develop new energy storage systems (ESS) suitable for any typical electrical conveyance (railways) and also for other propelled vehicles (electric vehicles and buses), in order to provide efficient urban public transport solutions that are real, attractive and competitive alternative to the combustion vehicles.

The current situation of the transport sector presents more problems than handle high power and energy, which is to increase the utilization index of the infrastructures and minimizing their energy consumption. Here is where ESTEFI (Estación de transporte intermodal eficiente y sostenible from Spanish) project will enter by means of an efficient and sustainable mix-mode station development incorporating new stationary and on-board energy storage systems (OESS), as well as the development of new power converters and energy management strategies. Thus, each energy demanding subsystem will conclude in this station (railways, electrical vehicle, lift and auxiliary loads), forming a unique micro-grid.

1.1.1 ESTEFI

The ESTEFI project tries to develop a substation solution which works as efficiently as possible, supplying the public transport needs within urban centres through a new mix-mode concept (concentrating tramways, buses, lifts and electrical vehicles) which will incorporate in an operational manner accumulation technologies. So making it is possible to offer to the urban transport operator a more sustainable and secure station, which will minimize the energy consumption of the whole installation. Hence, reducing the infrastructure cost by 30%, with a hired power reduction up to 50% and thus achieving an unprecedented energy saving in urban centres as internal documents shows [3]. Hence, the greenhouse emissions could be reduced according to the EU plans[2], which aims to reduce them up to 80% in 2050.

This project is carried out for a company consortium formed by Spanish companies from the railway sector (CAF Power & Automation and CAF Turnkey & Engineering), Mobility sector (Orona), Energy Storage Systems sector (Tecnicas Reunidas S.A. and AMOPACK) and from electric sector (SICA S.A.). It is subsidized by the CDTI (Centro para el Desarrollo Tecnológico Industrial from Spanish) by 80% of the total budget. It will last 3 years (2015-2018).

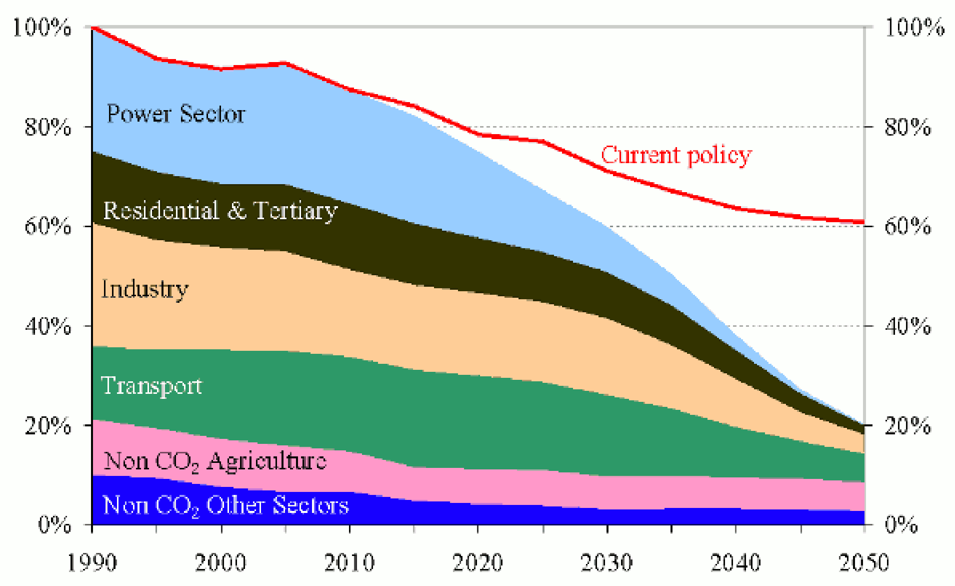

Figure 1-1: Possible 80% cut in greenhouse gas emissions in the EU (100%=1990). [2]

1.1.2 Mix-mode stations

As it was aforementioned, mix-mode stations connect different conveyances such as the railway systems (metro, suburban, tram), with road-vehicles (taxi, bus, utility vehicle) and other urban mobility devices, such as lifts and escalators. However, nowadays the mix-mode stations incorporate in their grid each of the mobility services in a isolated manner, what implies the electrical network of the station must be

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[2] COM(2011) 112 final - 2011/C 376/20 - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a roadmap for moving to a competitive low carbon economy in 2050.

oversized in order to guarantee the maximum power demand of each load.

Moreover, the incorporation of new technologies such as Electrical Vehicles (EV) and urban buses (hybrid or electric ones) causes mix-mode stations have to adapt to the new energy needs, what without prior planning suppose more feeders, increasing the power hired and the infrastructure cost. Look at Fig. 1-2 (a) to see how mix-mode stations were planned.

This is what is expected to be avoided with ESTEFI project, reducing the infrastructure and electrical equipment oversizing, decreasing thus the absolute energy consumption by means of ESS by 30%. Besides, it will allow, thanks to the ESS, adapting the energy consumption to the instant cost and reducing thus, the contracted power (20% in trams and 70% in lifts), with the incorporation of fast charge vehicles. Fig.1-2.b) shows its scheme.

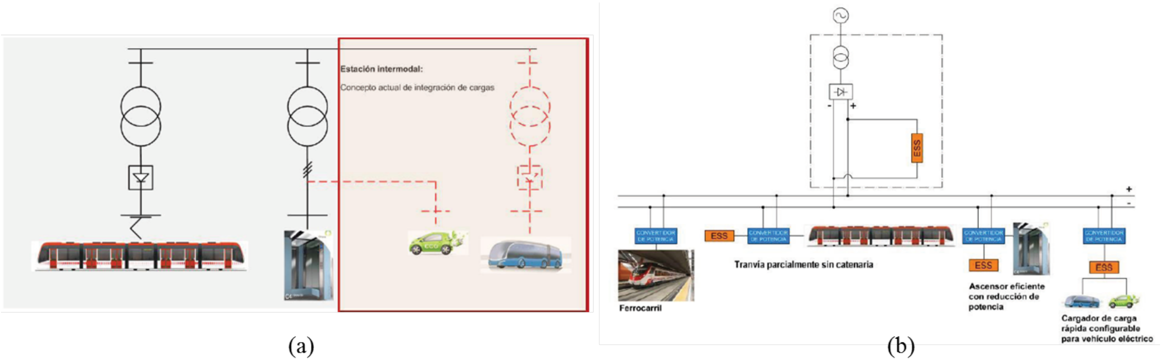

Figure 1-2: (a) Current intermodal station scheme. (b) Future intermodal station scheme with ESS. [3]

1.1.3 RailNEOS 2.0

Within the ESTEFI project, CAF Turnkey & Engineering (CAF TE) (beside to other partners), which is the collaborator company with this master thesis, is interested in achieving a new efficient electrification infrastructure for mix-mode stations. This will be done by studying how infrastructure influences the total energy consumption of the substation, taking into account the possible integration of accumulation devices (on-board and off-board). So, sizing accurately the needs of any mix-mode stations.

For simulating all these possible cases, CAF TE, beside University of Oviedo have developed a web tool called RailNeos 2.0, which is a versatile and comprehensive energy planned and management tool, with a total budget of 91000 €.

This tool is an update of the previous simulator called RailNeos 1.0 (also developed by University of Oviedo for another project), which although it worked fine, was quite rough and limited (only working for railways systems). In addition, this program was based on Matlab (licensed software), with an unintuitive and unfriendly interface with new users, besides that each simulation could take hours to finish, and now with RailNeos 2.0, the simulation can last only few minutes.

RailNeos 2.0 has been developed to have an useful user interface with the possibility of depicting all electrical variables, in order to study and understand the behaviour of the system. Once a railway system is simulated, the different variables can be extracted in db (data-base) format or in csv format for being read in excel.

This tool can be used as support when it comes to helping CAF TE customers, as well as for designing operation plans for the operators (this is part of the future strategy of the company, in order to extend its services and becoming in a mayor player on this sector). However, where this product is more powerful, is in the application of the tool to stations already operative. CAF TE will be able to help to the operators to decrease operating expense (OPEX), thanks to the detailed study of the whole system, resizing of maximum power requirements and sizing of the ESS to be installed.

Nowadays the development of this tool is finished, but it is not so tested. This will be one of the aims of this project, where the tool will be validated by comparing the results of several railway systems from both programs, RailNeos 1.0 and RailNeos 2.0.

Notice that although this tool has been developed in the ESTEFI frame, it is planed to be improved in future by the inclusion of different simulation options, such as train simulation and the AC infrastructure simulations.

1.2 Objectives

Once the topic of this project is put into context, the expected objectives to achieve will be enumerated just below:

1. Theoretical description about how railway systems work. From the type of system point of view (tram, metro...) up to the railway infrastructure point of view. Everything will be explained in a simplified manner (for more information, there will be some references at the end of the document).

2. Understanding and seeing how the different simulation tools work in order to simulate a complete railway system with RailNeos 2.0. This will take into account RailNeos 2.0 and Itiner (with a small summary of how it works).

3. Validation of an actual railway system (in this case belonging to Málaga suburban train) in RailNeos 2.0, and thus starting to actively use the tool and close this part of the ESTEFI project (for the complete validation more railway system were used, however in this project only one is included). After the validation is done, a small analysis of the system, in order to understand better how these systems work. Then some variations in it will be done, in order to know how they affect to this railway grid.

4. As personal objective, understanding how sqlite databases work, and how to export them into Matlab, for processing the data, and extracting valuable information and conclusions.

1.3 Structure of the thesis

The present master thesis is divided into 7 chapters, being each one of them focus on the following information:

- **Chapter 1:** In this chapter, an introduction of the master thesis topic has been done with an individual description of each one of the proposed objectives.

- **Chapter 2:** Along this chapter, the different railway system are reviewed, with a little explanation of each of them (metro, tramway, suburban...)

- **Chapter 3:** In this chapter, the different parts of the railway infrastructure are going to be studied. This will be the railway tracks, the over head line equipments and the substations.

- **Chapter 4:** Small explanation of the different simulation programs (ITINER and RailNeos 2.0).

- **Chapter 5:** Validation of a real railway system in RailNeos 2.0, through the comparison between result of RailNeos 1.0 and RailNeos 2.0.

- **Chapter 6:** Analysis of a real railway system, based in the suburban train from Málaga. In this chapter, an explanation about how these systems work will be done. After that, some variations of the grid will be done, in order to see how they affect to the railway network.

- **Chapter 7:** Finally, in this chapter some conclusions are extracted, and also, future works regarding this master thesis topic are described.

Chapter 2

Railway Systems

2.1 Introduction

Railway infrastructure system is understood as all transport system which transits railways tracks (iron or steel), as well as the physical infrastructure and its civil work. They are used both for transporting goods and/or people. Due to their features, railways have a great capability that can be extended to cover any distance in any environment (urban, suburban, periurban, regional and interurban), with a widely range for passenger's transportation (usually 1500 km). This range can be much greater for freight [4].

The main advantages of these kind of transportation systems are:

1. Great capability for making massive transports.
2. Lower environmental impact.
3. Capability to compete with the plane in certain distances.

These traction systems can be fed by electrical energy or by diesel fuel. In Europe, the electrical feeding systems prevail, whereas in America most of the interurban lines are fed by diesel. Notice this project is only focused in the electrical railway systems, which is the most widely used in the world.

There are several kind of railway systems such as tramways, light-rails or light metros, metropolitans, suburban trains, interurban, high-speed trains, monorails, suburban railway, magnetic-levitation trains, cable-ways, etc.

This chapter is dedicated to the explanation of the aforementioned railway systems (from trams up to high-speed railways) in a brief and descriptive manner, in order to understand their main characteristics and how they work and thus putting into context the project.

2.2 Tramways

Modern tramways are steel wheel electric trains which run almost exclusively within urban roads sharing the same infrastructure as the rest of the road traffic or moving on a specially built corridor for them, but without being bounded in one site. They usually work in towns from 100.000 - 500.000 habitants, being able to carry about 125.000 passengers/day, serving distances usually in the range of 5-20 km, with distances among stops approximately of 400 m.

Tramway's cars have a length between 18 and 40 m, with low floor train, having most of the components on deck. Fig. 2-1 shows an example of tram, an older and another newer one. Furthermore, tramways can reach commercial speeds[1] between 18 and 25 km/h and maximum speeds between 30 and 50 km/h.

Nowadays, this urban transportation system have resurfaced in many town around the world, having a great importance their physical appearance, with most of their hidden switchgear, in order to do not disturb the aesthetics of the city.

Figure 2-1: Left: Old tram from Avilés [5]. Right: Current Bilbao tram [6].

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[1] The commercial speed of a train is the result of dividing the distance from origin to destination by the time which spends travelling, including the stops.

Within the trams, the light-rails or light metro can be included. They use the typical metro's infrastructure in terms of the place they operate, but the rolling stock are basically trams. They could also be included in metro category instead of trams.

2.3 Metro

The metro (or metropolitan) is a people transportation system which exclusively uses electric traction with the traditional steel wheel on a rail guidance system, within a exclusive corridor where the largest part of which is under the city, and in any case, it is separated from the roads and urban streets (see Fig. 2-2 as an example). It is a conveyance which operates inside the town or among urban centres close to each other. This transport system presents a high construction cost (€60-130 M/track-km). For that reason it is installed in cities with more than 300.000 habitants in order to obtain an assumable amortization in time. It also presents a high-frequency service, being able to transport 200.000 passengers per day [4],[7].

The metro's cars have a length between 60 and 120 m, which are a high-deck trains, having all the elements and devices in the lower part of the train. In this case, the distance among stops is approximately 800 m. Moreover, metro trains can reach commercial speed between 30 and 40 km/h and maximum speed between 60 and 90 km/h.

Figure 2-2: Left: Barcelona metro [8]. Right: Madrid metro [9].

2.4 Suburban railways

Suburban railway systems are used as electrical passenger railway transport system, in order to carry people within the geographical boundaries of large urban agglomerations, which are close to each other (Fig. 2-3 shows an instance of this kind of trains). Generally, they travel in a confined via, but on the surface. Depending on the frequencies, they can transport a large amount of passengers.

The suburban cars have a length between 80 and 200 m, with a low floor train, having most of the components on deck. In this case, the distance among stops is between 800 and 1500 m. They can reach commercial speeds between 35 and 50 km/h and maximum speeds between 80 and 130 km/h.

Its range can exceed 100 km up to 150 km. Depending on the length they cover, the nomenclature changes. As [4] says, distances from 30-50 km they are designated as commuter or urban rail, whilst when they cover greater lengths, they are called "regional" railways.

Figure 2-3: Suburban railway [7].

Within this category, the interurban railways can be included, because the main difference they have against the suburban railways is the distance they can travel. In fact, the same train are used for both applications, even thought the voltage needed for operating is different. Normally, these trains are prepared for working in a multi-voltage operation, and even with multiple railway track width.

2.5 High-speed railways

High-speed railways are also electrical railway transport systems used to carry people between far off big urban centres. In the same way than most of the other railway system, generally, they operate in a confined via on surface. Because of their great speeds, the sharp curves are not allowed, having to travel in a straight line as much as possible. Therefore, tunnels are quite used.

The high-speed cars have a length between 100 and 400 m, with a high floor train, having most of the components on the low part of the train. In this case, the distance among stops is between 10 and 300 km, being able to reach commercial speeds between 100 and 225 km/h and maximum speeds higher than 140 km/h until more than 300 km/h. Fig. 2-4 shows the OARIS which is a the high-speed train from CAF.

Figure 2-4: OARIS from CAF [7].

2.6 Other types

In order to conclude with railway systems, some railways types are going to be named, which can be found them in the current railway installations in a less frequent manner, and some of them are still under development. These other types can be seen in Fig. 2-5.

2.6.1 Monorail

The monorail is an electrified light rail passenger transport system, which consists of a single rail. This transport mode is formed with a small number of vehicle (2-6) and in most cases it moves via rubber-tyred wheels, on an elevate permanent way. It only covers short distances (10 km), with maximum speeds around 60-90 km/h [11], [12].

2.6.2 Funicular

The funicular or cable railway operates employing two vehicles which are pulled on a slope by the same cable which loops over a pulley wheel at the upper end of a track. One of the vehicles is ascending while the other one is descending.

This system connects distances lower than 5 km with continuous gradients between 300 ‰ to 500 ‰ [4], [13].

2.6.3 Magnetic-levitation railways

The magnetic-levitation railways or MAGLEV is a transport system which includes the suspension, guide and propulsion of trains, by using a great amount for magnets for that task. In order to achieve it, as [17] explain, it uses the ”Meissner effect” taking advantage of the superconductors features. Thus, these trains could reach speeds up to 6440 km/h [18]. Nowadays, some tests in Japan have been carried out, achieving speeds up to 603 km/h [20]. It is still under research.

Figure 2-5: Up: Funicular [14]. Right: Monorail [15]. Left: MAGLEV [16].

Chapter 3

Railway Infrastructure System

3.1 Introduction

In this chapter, the basic railway infrastructure needed for the operation of trains are going to be reviewed and explained. The covered topics will go from the rail tracks up to the substation, including their switchgear. Moreover, the different types of energy accumulators used in these system will be reviewed (on-board and off-board accumulators).

3.2 Railway tracks

The trains run through the railways tracks thanks to the friction between the steel wheels and the rail, being necessary the traction force created by the electrical machines. The rail and the wheels have a low rolling resistance, making the train move on through the tracks. However, this presents some problems as the high braking distance and the limitations in slopes and ramps.

Even so, these railway systems are fairly good and versatile because of the great transport capacity, with ease of automation and as the trajectory has being previously defined (with one degree of freedom), it is quite secure at high speeds.

As [11] says, the railway tracks of the trains can be studied from two viewpoints. One from the point of view of the civil infrastructure (tunnels, bridges, railway track layout...), and the other one, from the point of view of superstructure, which is formed by the railway tracks.

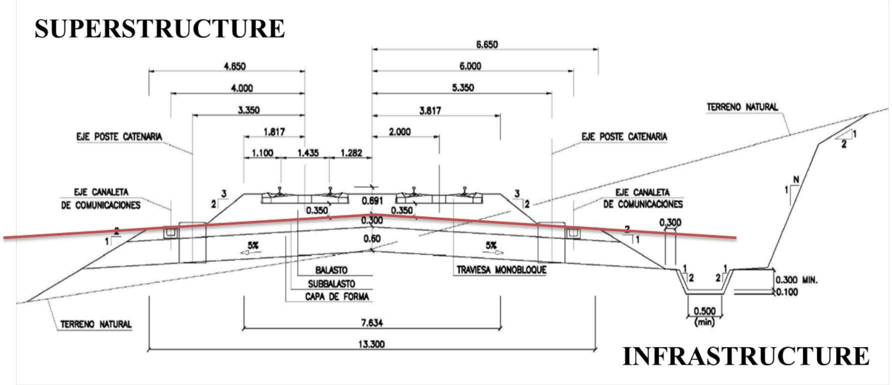

Figure 3-1: Infrastructure and superstructure [19].

3.2.1 Track gauge

In the past, the track gauge of each country or railway company was different of each other. This diversification was not a critical factor in local traffic. However, during the industrial revolution required the interconnection among lines, in order to circulate any train (does not matter their origin) in any parts of the world. For that reason, the international track width was created by the International Union of Railways (UIC) (see Table 3.1 to see the different railway track widths). This track width is 1435 mm, which is habitual in metro railways [21].

In Spain, as [11] says, the track width of RENFE is 1668 mm, but FEVE has a 1006 mm, so they are not compatible between them. The international width track is habitual in metro railways, minus in low exploitations as Bilbao and Valencia, which has a narrow-gauge[1]. This narrow track presents a clear advantage, which is the lower investment in infrastructure, however the price to pay is the lower passenger transport capacity.

Besides, in other countries as Russia, they use a track gauge of 1524 mm, and in Chile and Argentina 1676 mm. As it can be seen, depending on de country, there are still different railway track widths.

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[1] The narrow track is defined as the lowest railway track width of a country.

Table 3.1: Railway track width

Via	Width (mm)
UIC	1435
Renfe	1668
FEVE	1006
Chile, Argentina	1676
Russia	1524

3.2.2 Rails

The rail is a laminated steel rod, whose shape is like a mushroom. This element belongs to the superstructure and is in charge to endure the weight of the train, guide it and also, it is used as return of electrical circuits of both catenary and signalling [11]. The most used is the Vignole rail (see Fig. 3-6.a), which is composed of 3 parts (the railhead, web and foot), although there are other quite used like the grooved rails (see Fig. 3-6.b), which is more used for trams.

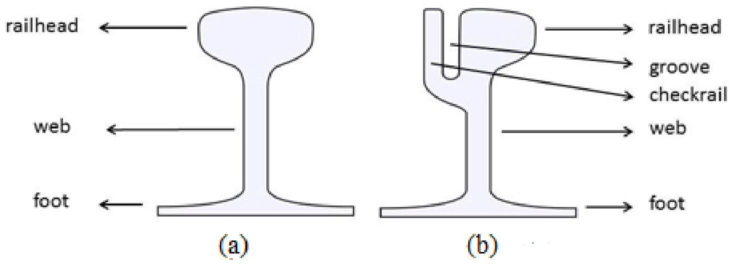

Figure 3-2: (a) Vignole rail. (b) Grooved rail. [22]

The connections between rail sections can be done by welding (thermal aluminium welding or other technique) or even joints.

3.2.3 Railway sleepers

Rail sleepers are elements which are placed in the traversal direction to the railway track direction. They endure the rail, comprising a link between the rail and the ballast [11]. Their main functions are keeping the width of the track, as well as their levelling and desired inclination. Furthermore, they must withstand the efforts created by the train, in the three directions. Their last task is to provide electrical isolation between rails.

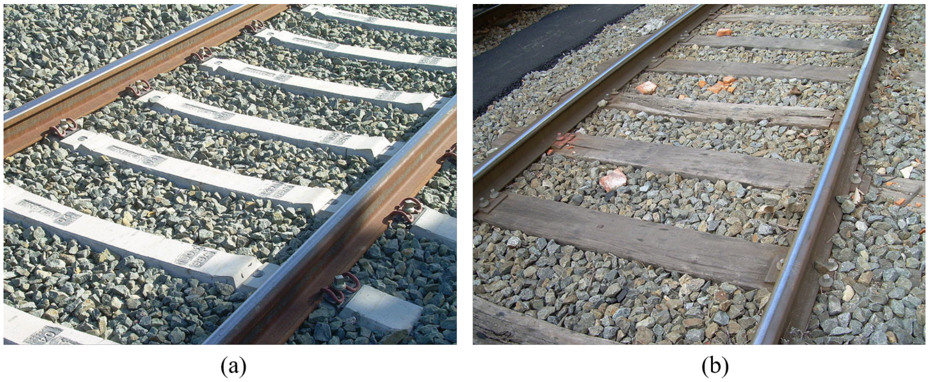
(a)
(b)

Figure 3-3: (a) Pre-stressed concrete sleeper. (b) Wood sleeper. [19]

Normally, they are made of two different materials:

1. Wood: Nowadays, they are hardly used because of the advantages of the concrete sleepers. Their advantages are their great strength against accidents, but not versus the age or other external agents.

2. Pre-stressed concrete: There are several kind of models, which improves the behaviour of the wood ones. For instance, the mono-bloc sleepers improves the resistance against alternative efforts, decreasing the sleeper thickness. On the other hand, the two ball sleepers in order to reduce cracking. Notice there are other kinds of concrete sleepers.

3.2.4 Fasteners

Fastener is the element which fixes the rails to the sleepers, or the rails to the ballastless track, making possible the structural continuity of the railway track. It is one of the critical elements in terms of maintenance cost, because its revision and repair needs a lot of workmanship. Its main function is to absorb and transmit the vertical and horizontal loads, avoiding the overturning of the lane. It also keeps the vertical tightening, in order to avoid the loss of contact between the rails and sleepers, maintaining the same track width, improving the elasticity between rails-sleepers [11].

Notice that depending on the kind of sleeper, there are different types of fasteners as Fig. 3-4 shows.

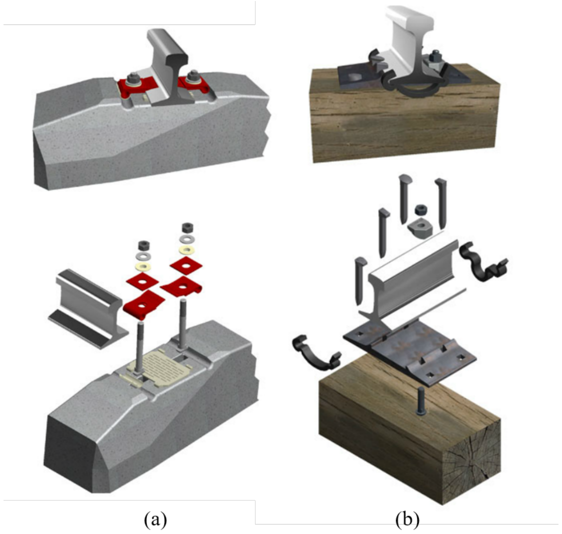

Figure 3-4: (a) Fastener for concrete sleepers. (b) Fastener for wood sleeper. [19]

3.2.5 Ballast

Although the railway tracks are installed currently through a plate (ballast-less track), there are still many kilometres, even in construction, which used ballast. It is a granular element on which the sleepers settle. The ballast transmits and distributes the loads, in order to do not exceed the admissible tensions in the lowest layer. Thus, the ballast embeds the sleepers in order to avoid any movement of the railway track and protecting the platform.

3.2.6 Ballast-less track

The slab track is a kind of railway which has as goal to achieve a great quality [23],[11], decreasing the maintenance costs. As its name says, they do not use ballast, and consists of a concrete 's plate which transmits to the platform efforts uniformly distributed and lower than with ballast. The problems these ballast-less tracks present is the higher construction cost and more difficult maintenance in the platform.

Figure 3-5: Ballast-less track [19].

3.2.7 Stations

Within this subsection, the different train stations will be named and classified, depending on the functionality, the type of infrastructure and the distance between interstations. They are shown in Table 3.2 [19].

Table 3.2: Classification of stations

Functionality		Structure	Distance between interstations	
Terminal station	Interurban station	Level station	Tram	250-1200
Line station	Rural station	Elevated station	Light metro	350-1500
Interchange station	Tram stop	Underground station	Metro	500-2000
Halt			Suburban	2000-8000

3.2.8 Rail track complements

Railway tracks can have many configurations, and over them circulate several trains with different itineraries. In order to avoid problems between trains, some junctions were implemented:

- Turnout (see Fig. 3-6.a): It allows an itinerary to branch off into two or more router, the axes of the roads being tangent to each other.

- Crossing(see Fig. 3-6).b: It allows the intersection of two routes and therefore the axes of the roads are cut.

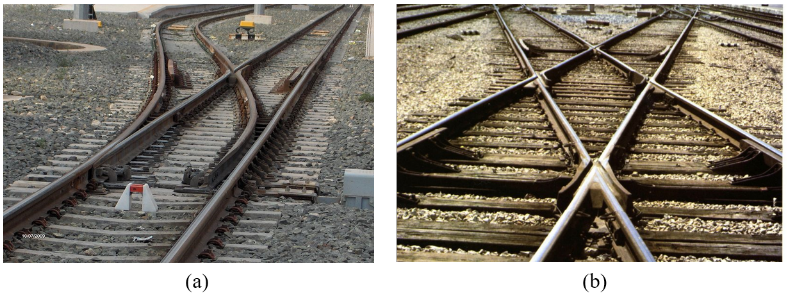

Figure 3-6: (a) Turnout. (b) Crossing. [19]

3.3 Electrical energy types for railway systems

Nowadays thinking about railway system is thinking about electrical energy as primary energy, being this energy obtained from the railway power supply system (RPSS) or from an on-board accumulator. The other primary energy types, such as diesel or hybrid, are out of the scope of this project.

At the beginning of the railway electrification, the direct current (DC) was more used; because of the effort-speed curve of the series-DC machines were more favourable in these applications, as well as their easy of control. Therefore, approximately half of traction system in the world use DC current since these days, although with the emergence of power converters, this has changed; becoming the AC machines the dominant technology.

DC system has as disadvantage its low voltage level (from 600 to 3000 V), what means there are large currents at high powers (many losses and voltage drops) and its cables will have higher sections. In spite of its drawbacks, it is worth for short-distance applications (metro, suburban, tramways . . .), having a reasonable cost in comparison to AC systems, as [25] shows. Another reason can be the difficulty of the railway industry to apply changes in their designs, and the way of doing things, since it is a fairly traditional industry.

Nevertheless both AC and DC systems are quite extended all around the world. Currently, many of the installations that are in construction around the world use both, using the AC for high-speed applications, and DC for the other applications, in general. The use of AC systems was achieved thanks to the development of power electronics, and the invention of new control techniques, allowing control the AC machines in a similar way than DC ones as [24] shows. Besides it allows adopting higher-voltage values (AC allows using transformers), what means to reduce the level of current and hence reducing losses. This has also allowed the integration of these railways systems in industrial networks.

The voltage values for railway systems were standardized, in order to control them, so depending on the system (AC or DC), several voltage levels exist as Table 3.3 shows. These values are according to EN 50163.

Table 3.3: Voltage types in European railways according to EN 50163 [26].

Feeding type	V_n (V)	V_{min2} (V)	V_{min1} (V)	V_{max1} (V)	V_{max1} (V)	V_{max3} (V)
DC 600 V	600		400	720	800	-
DC 750 V	750		500	900	1000	1270
DC 1.5 kV	1500		1000	1800	1950	2540
DC 3.0 kV	3000		2000	3600	3900	5075
AC 15 kV 16.7 Hz	15000	11000	12000	17250	18000	24300
AC 25 kV 50/60 Hz	25000	17500	19000	27500	29000	38750

U_n	Rated voltage.
U_{min1}	Permanent minimum voltage.
U_{min2}	Nonpermanent minimum voltage. Maximum duration 2 min.
U_{max1}	Permanent maximum voltage.
U_{max2}	Nonpermanent maximum voltage. Maximum duration 5 min.
U_{max3}	Highest overvoltage of long duration (t = 20 ms).

In the current section, some of the most common general feeding schemes will be reviewed, taking into account they are the same independently of RPSS type (AC or DC). After that, both AC and DC traction systems will be reviewed.

3.3.1 General feeding schemes

As [27] explains, the electric traction power supply are divided in electrical sections, where at least one substation or feeder supplies each electrical section. Within their own definition, their main characteristic arises, which is none other than the capability to be easily isolated form the rest of the system in case of failure or permanent short circuit. That means the whole traction system can operate without the isolated section with none problems. The different electrical sections prevent successive substation supplied electrical sections with different voltages being connected. However, in order to be operational, two different sections can be interconnected thanks to track sectioning stations by means of section insulators or insulated overlapping sections. If more tracks must be connected, track paralleling stations can be used.

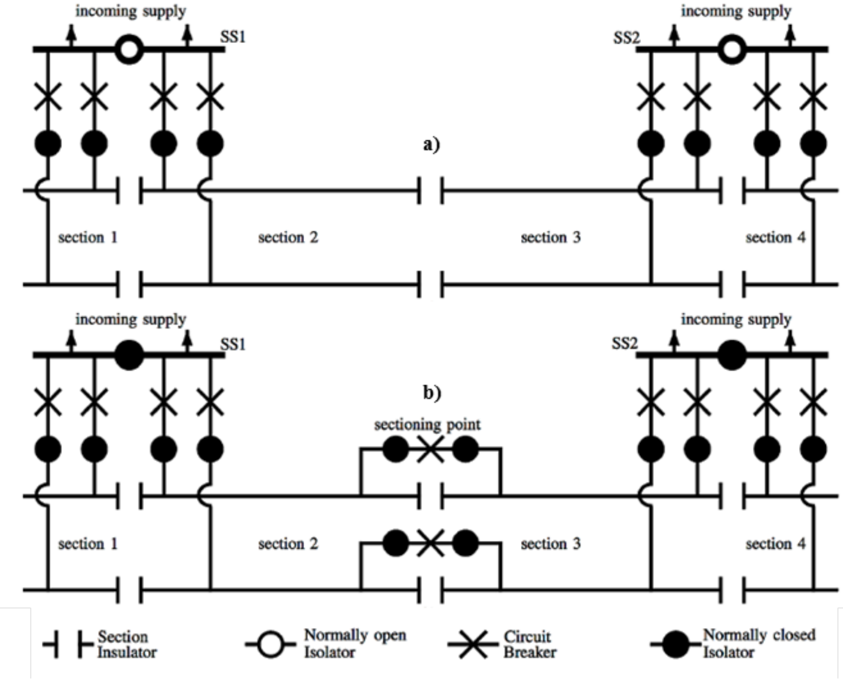

Figure 3-7: Representation of most common feeding schemes in railway power supply systems: a) Single-end feed. b) Double-end feed. [27]

Fig. 3-7, which was developed by [27], shows two different feeding schemes, which for this example, the author a double track line has been considered, and trying to simplify things, it has been represented the contact line schemes without the returning circuit. Fig. 3-7 a) shows the single-end feed, where all sections are electrically independent between the contact lines is isolated, having each substation two incoming supply feed, where each of them supplies just one section. In case of fault in one of the tracks, it can be rapidly isolated because there is one circuit breaker per track and section.

Fig. 3-7 b) depicts the double-end feed with longitudinal coupling, where all sections are electrically connected. The two tracks of sections 1 and 2 are cross-coupled in substation 1 and the two tracks of section 3 and 4 are cross-coupled in substation 2. Furthermore, a longitudinal coupling of both tracks of section 2 and 3 independently exist, by means of a sectioning point. Because of this, the voltage drop in this scheme is lower than the previous one. Notice that in this case, the power flow is not unidirectional like the previous case, and it cannot be applied when two adjacent substations are supplied by voltages with different magnitude and angle.

3.3.2 AC Traction systems

Although the use of railway AC systems is increasing currently, especially in its main application, which is the high speed, they are not included in this project, in case of RailNeos 2.0 simulator. However, these systems are expected to be included in following years, so a brief explanation of the different AC feeding systems is done in this section.

In terms of AC feeding systems, the most common is the one based on 25 kV and 50 Hz, except in countries like Germany or Sweden where the most used is based on 15 kV and 16.7 Hz. Both systems are quite similar in many aspects except for the way they are fed. Whereas 25 kV, 50 Hz systems are fed by the distribution or transport network by means of power transformers, the 15 kV, 16.7 Hz systems are fed through their own single-phase transmission connected to dedicated power plants or through the transmission system with frequency converter stations (central stations or decentralized stations – rotating/static converter stations) as [27] and [25] explains.

Depending on the selected power supply system, different feeding schemes can be used. In case of 15 kV, 16.7 Hz system, all sections of the system are fed with the same voltage, so the traction network could be operated with longitudinal coupling between sections, on which can be used also in 25 kV, 50 Hz system if transformers with the same voltage angle. This is something that sometimes must be avoided for balancing the voltages, having to use single-end schemes to avoid short circuit current provoked by the different voltages in the adjacent sections.

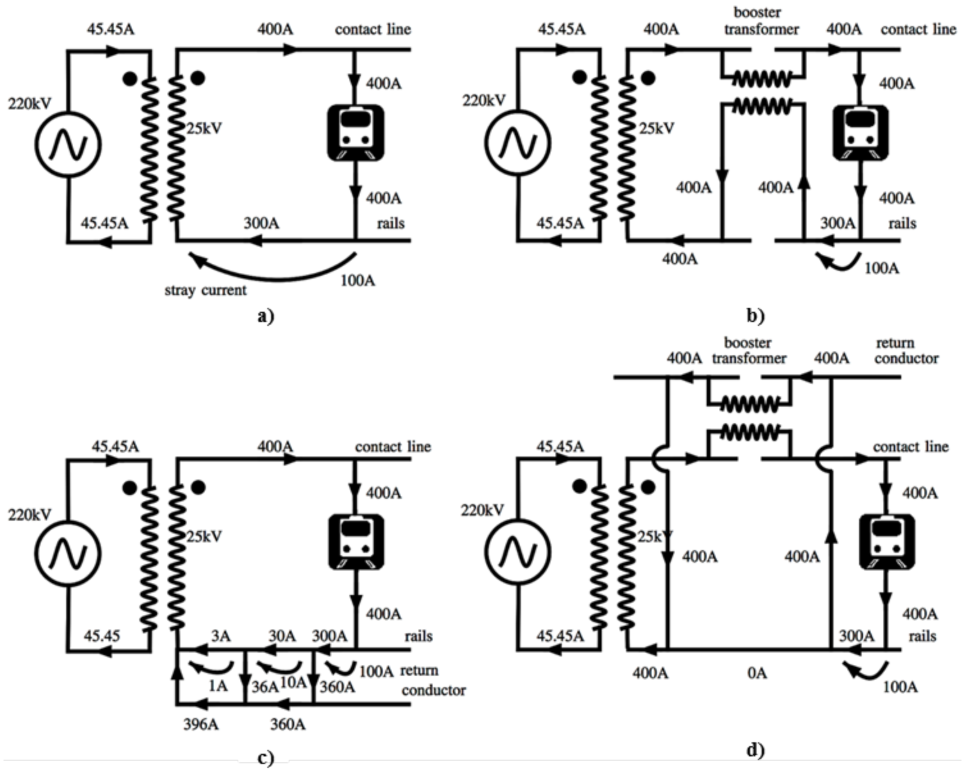

Figure 3-8: AC 25kV feeding systems [27].

Fig. 3-8 (extracted from [27]) shows the four typical configurations of AC traction systems, where all of them are supposed to be 25 kV and 50 Hz systems. As it can be seen, the simplest scenario is depicted by a), which is known as direct connection, using a single-phase power transformer. The primary winding is connected to the distribution grid side, and the secondary winding is directly connected to the railway system side. This solution provides a low cost and simple solution. However, as it can be seen, it gives rise to an enormous returning current, which as it will be explained later on, the current returns through rails. This fact causes dangerous contact voltages, and as the rails are not isolated, there is a nonnegligible amount of stray currents.

Fig. 3-8 b) partially solves this problem, because booster transformers are installed between different isolated sections of contact lines and rails, forcing the current going through the rails and removing thus the stray currents.

In case of the configuration depicted in Fig. 3-8 c) the return conductor (or rails) reduces the return impedance and also the stray currents because most of the current will return through it. This solution can be combined with the boost transformers in order to obtain the solution that d) shows, obtaining thus the best solution, where the stray currents are eliminated, as well as the dangerous touch potentials in the rails.

Although the 25 kV, 50 Hz system is a good solution, another configuration was designed for being used in larger length of overhead lines without exceeding the maximum allowable voltage drop. This system is called 2x25 kV and 50 Hz bi-level that can be seen in Fig. 3-9. In this configuration the secondary windings of the power transformer placed at the substations are equipped with a central tap connected to the rails as [27] explains, being one pole connected to the contact line (positive feeder) and another one to the negative feeder. Here, the voltage between the positive feeder and the rails will be 25 kV and between the negative feeder and rail -25 kV, obtaining a voltage level of 50 kV between both feeders. However, this not affects to the train, because it will see 25 kV between its terminals (so the same trains can be used in both systems). The most distinctive feature of this scheme is the use of autotransformer with an unity turn ratio as Fig. 3-9 shows. The advantages of this scheme are the currents through the rails are reduced, as well as the rails potentials and its losses.

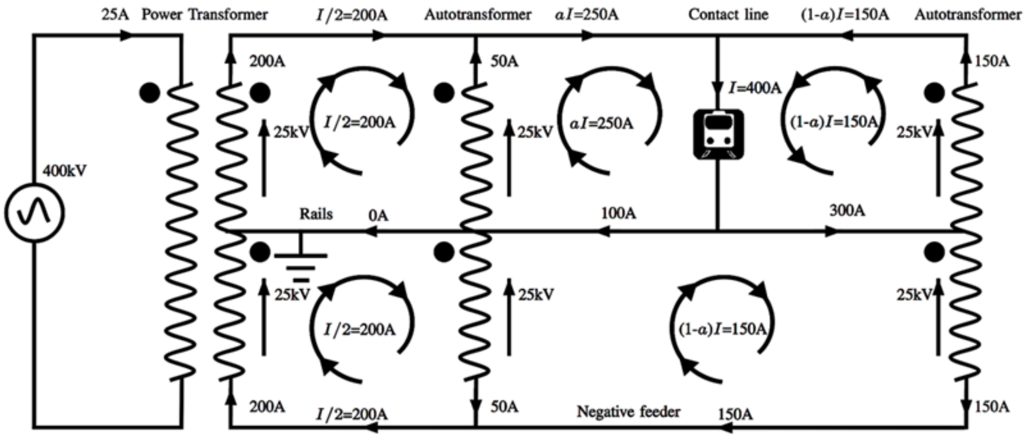

Figure 3-9: AC 2x25kV feeding systems [27].

Notice the bi-voltage systems are not restricted to 25 kV system, if not they can be used in 15 kV, and even in DC tractions systems using the same scheme, but in this case, replacing the autotransformer by DC/DC controlled converters.

3.3.3 DC Traction system

The DC tractions systems are connected to the distribution network though power transformers and AC/DC rectifier units. These devices can be of two configurations, such as six-pulses or twelve pulses noncontrolled rectifiers, as Fig. 3-10 shows. These rectifier systems can be controllable (by replacing the diodes by power transistors, such as MOSFETs or IGBTs), when the substations must work in reversible way injecting power from DC traction systems into the AC network. This occurs when trains, with regenerative braking, circulate within DC traction systems.

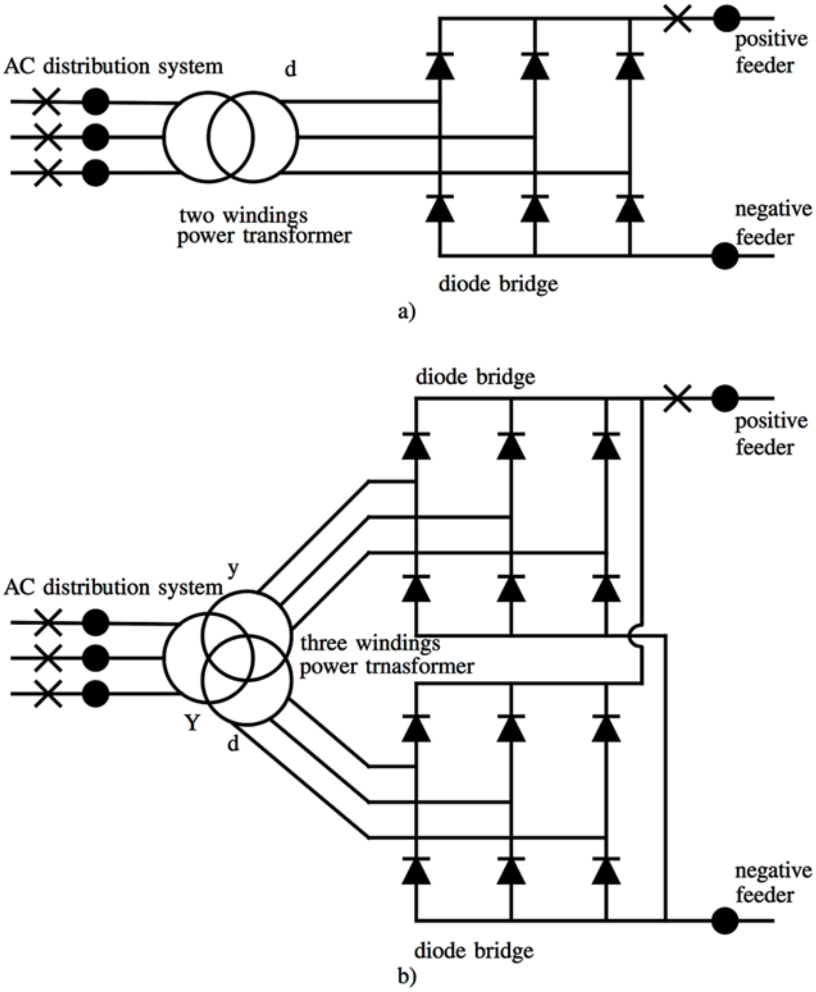

Figure 3-10: Typical AC/DC conversion systems for DC traction systems: a) Six-pulse noncontrollable rectifier. b) Twelve-pulse noncontrollable rectifier. [27]

If this energy is not recovered by the AC part, or consumed by another traction unit, the contact line voltage will increase up to reach a given threshold, which is when the controlled rectifier, if any, will inject power to AC part. If there is not a reversible substation, when the energy overcomes the threshold, this energy will be burnt into the brake resistors. In DC traction networks, is possible to operate the system using the single-end feeding scheme, however, the double-end feeding is also possible in most of the cases. In case of grounding systems in DC traction networks can be classified in three basic types.

1. The solid grounded connection of rectifier negative pole leads to avoid high voltage potential in the rails; however a big percentage of returning current is stray current, generating interferences in telecommunications and corrosion in metallic pipelines.

2. One possible solution is using isolated negative feeder, but dangerous contact voltages can arise in the rails.

3. Using a system that can connect or disconnect from the ground the rectifier negative pole. This system is normally isolated, so the rails are under voltage and the stray current very small. When this voltage starts to be important, the negative pole is grounded, and the stray current comes into stage. This connection is done by semiconductor devices.

3.4 Electrification and current collection

The traction energy is provided through the high-voltage lines, where once it is transformed and rectified (in case of DC), the energy is distributed through the electrification and ancillary systems. After that, the energy is delivered to the railway rolling stock, where its traction electric machines transform the electrical energy into mechanical, moving on through the tracks. This electrical energy also feeds the ancillary services of the train.

3.4.1 Catenary

The electrical energy flows through the overhead contact lines in the railway electrical power system. The overhead contact lines are usually knowns as catenaries, although catenaries are split in several devices as it will be seen below (contact wire, suspension wire...). This forms one of the most widespread top electrification systems, although there are more types, as it will be seen later on. Note the following overhead contact equipment is described for DC systems, although, both DC and AC are quite similar in this topic.

Contact wire

This is the fundamental element of the catenary, because of it is the active wire on which the pantograph goes rubbing and providing the needed energy for the traction and ancillary systems. Its habitual sections, which in turn are standardized are 107, 120 and 150 mm^2, being similar as Fig. 3-11 tries to show [11].

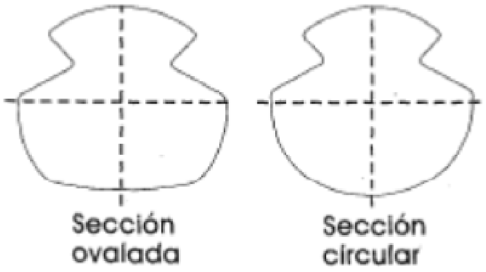

Figure 3-11: Contact wire [28].

The material they used is normally electrolytic copper or copper-silver, copper-magnesium, copper-bronze or copper-cadmium alloys.

Notice the contact wire of the catenary is displaced alternatively[2] from one to another side of the railway track axis, in order to avoid excessive pantograph wear. The maximum allowable displacement from the axis is 20-25 cm.

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[2] This is done by the registration arm, which connects the contact wire and the bracket.

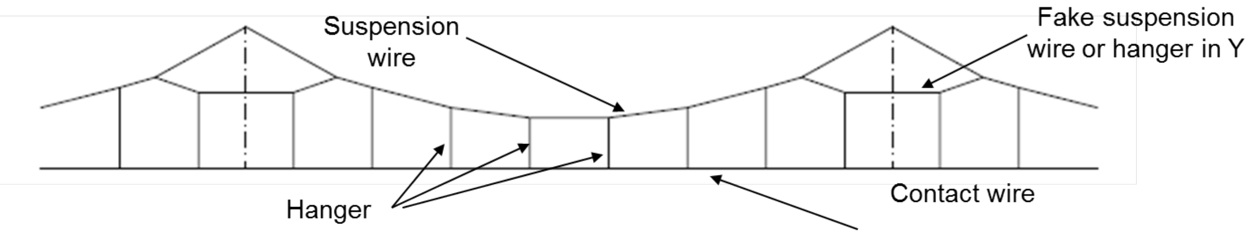


Figure 3-12: Hanger, suspension wire and contact wire system.

Suspension wire

Because of the contact wire cannot be tightened as it would be needed (in order to obtain a contact wire as much flat and horizontal as possible), because of the dangerous mechanical stresses on the wire, which can break it, the suspension wires are used. This wires also helps to withstand the weight of the cables, achieving the needed mechanical strain in the catenary.

As these cables cooperate in the transport of current, they must be sizing as the other parts of the catenary. Depending on the system, the habitual dimensions and materials are different, as Table. 3.4 shows.

Table 3.4: Suspension wire. Dimensions and material.

Type of current	Material	Size
DC	Cu/Bronze	299, 182, 153, 120, 95/184, 116
AC	Bronze	50, 65
High-speed	Copperwell	-

Hanger

These vertical cables made of copper or bronze take care of maintaining the contact wire height constant over the rolling surface [11]. They are between the suspension wire and the working thread as Fig. 3-12 shows. The element which connects both the suspension wire and the contact wire without interference of the pantograph is the splicing clamp.

They can be rigid or elastic, having a purely mechanical purpose or also an electrical conductor.

Feeding cable

This cable is used when there are lines with high traffic density and high consumption, because this can provoke dangerous warming to the whole cable set (see Fig. 3-13). Thus, the conduction section of the catenary increases, reducing the losses and the warming. It is connected periodically, each 100-300 m [11].

Figure 3-13: Feeding cable [28].

Poles and catenary gantries

These elements are responsible for mechanically withstanding all components of the overhead line equipment. The poles are fix to ground through concrete foundations, as Fig. 3-14.a tries to show. In case of catenary gantries, as Fig. 3-14.b shows, they group different catenaries. They are built when there is not room for assembling each catenary independently. There are several types of catenary gantries: Rigid or Funicular.

Bracket

It is the element which by leaning in the poles, allows install the catenary in the correct position. They can be of two types:

- Lattice brackets: They are connected to ground, therefore the cables are connected by isolators.

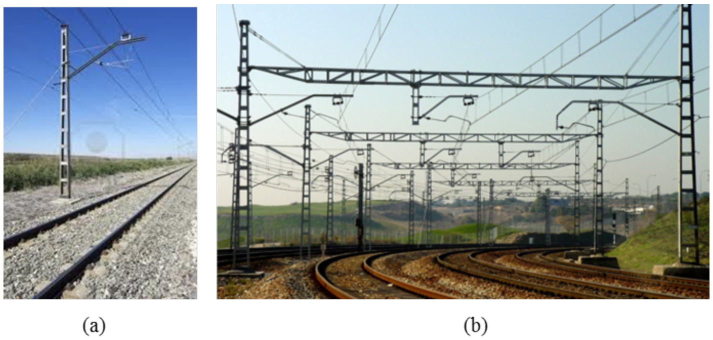

(a)
(b)

Figure 3-14: (a) Poles. (b) Rigid bent. [28]

- Tubular brackets: They are always energized, so they are connected to the posts by isolators.

Isolators

The contact wires must be isolated from ground, and this is achieved thanks to the isolators (they are usually made of glass, porcelain, etc.). Furthermore, these isolators will also have to interrupt the electrical continuity from one section to another.

Catenary canton

The canton term is used for naming the different sections that a catenary is subdivided. These sections usually have a length between 900 to 1200 m.

Each canton is mechanically independent from the other, therefore its mechanical strain is regulated by means of pulleys and counterweights. This system, when it is automatic, it is called compensation set [11] (see Fig. 3-15).

Normally, these cantons are electrically isolated from the others, but nevertheless they can be connected. When this happens, these are called ”electrical canton”.

Sectioning

When the catenary is electrically or mechanically interrupted with the neighbouring overhead line (OHL), it is said that there is a sectioning. Thus, it is guaranteed the isolation between catenaries through the air. On the other hand, when the OHL is electrically interrupted, but not mechanically, it is said that there is a section isolator.

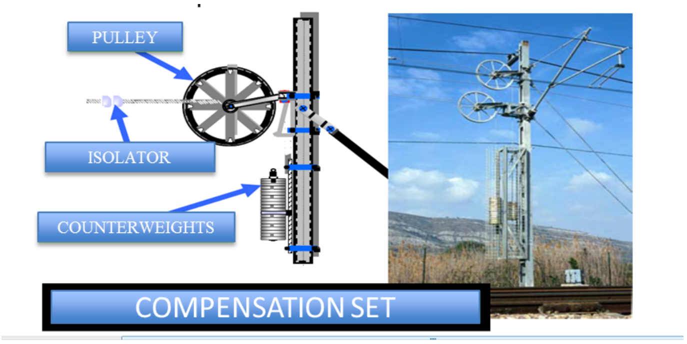


Figure 3-15: Cantenary canton with a compensation set. [28]

Disconnector

It is a device used for interrupting or restoring an electrical circuit. It is used for connecting or disconnecting the electrical cantons. The installation of these devices also allows the isolation of areas in failure, increasing the traffic regularity, and one of the most important, which is to facilitate the maintenance. The isolators work beside voltage detectors, which allow to know the presence of voltage in an installation.

3.4.2 Return

The current return is realized by the rails, and it is used to close the DC traction circuit. In DC the rail must be isolated from ground in order to avoid stray currents, although this depends on the application.

In case of AC, ground and return usually are connected, however, if the earthing is not properly done, the rail is energized. Besides, there is usually a guard cable for returning, having to make down-lanes every certain distance.

3.4.3 Other catenary types

In this subsection, different superior collection systems than the aforementioned described will be explained, such as the tramway catenary, the tunnel OHL and the rigid catenary.

Tramway catenary

This is the simplest system of OHL, where there only is a contact wire suspended in between two consecutive poles. It is used for low speed systems such as tramways, light metros and depots.

Tunnel catenary

The tunnel catenary depends on the shape of each tunnel or station, which impose constrains to the mechanical assembly, as [11] explains. The main difference between both tunnel and outdoor catenaries is basically the posts and brackets, being the other components practically identical.

Rigid catenary

In this system the current transmission is not done by cable, if not by means of a extruded aluminium rigid rail, which has a contact wire in its lower part.

The current flows through the rail as well as the cable, but the pantograph only touches the active wire (the pantograph is the same than the one used in flexible catenary applications). This catenary type is used in tunnels and places with limited gauge. This system reduces the installation cost and the civil work.

3.4.4 Third rail

The third rail is the eldest form of electric power supply to electrified railways. It is used to transmit energy to the trains in metro and urban railways [25]. It is based on a rail, conveniently isolated, placed at one side or in the middle of the driving lanes, always in confined tracks. From this rail, the trains take the energy for their traction by means of a collector. A scheme of different configuration is shown in Fig. 3-16.

This system is used in DC (in AC, it would precise higher isolation) and in railway lines with restricted access, since the high degree of danger.

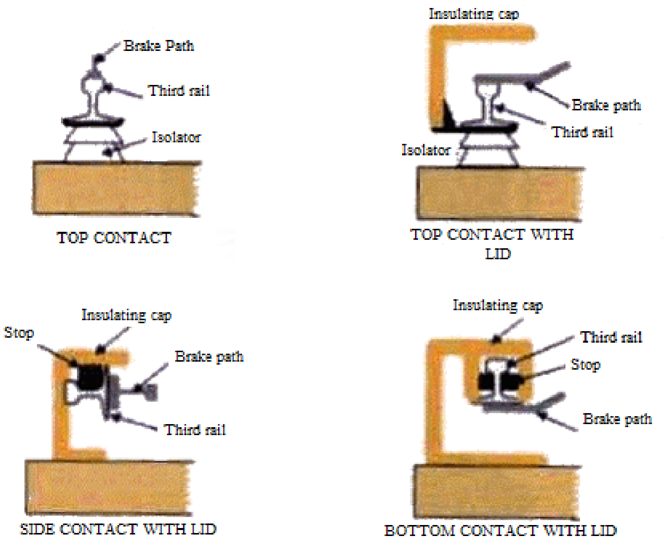


Figure 3-16: Third rail configurations. [28]

3.4.5 Third and forth rail

This system has two extra rails, where each of those have a different voltage. For instance, one is fed at +300 V and the other one is at -300 V, obtaining a total voltage of 600 V.

This system is used in monorail applications and in some metro installation around the world (as London metro). In monorail's applications, the vehicle circulates through concrete beams, so it is required an additional rail for returning the current.

3.4.6 MAGLEV

The magnetic levitation systems uses a high number of magnets for levitation, propulsion and guidance of the trains, based on the interaction among magnetic fields due to the "Meissner Effect" [17]. As there is not physical contact between both train and rails, it is faster and quiet. The problem is the high cost of the system, in terms of infrastructure and the enormous amount of electrical energy it needs, in order to create the great magnetic field it needs.

3.4.7 APS - Ground level power supply

Alimentation per sol (APS) system (expression of French origin), which means ground level power supply is based on a electronically sectioned third rail as [30], [31] explain. This system was developed by Alstom, on which was installed in Bordeaux (France) in 2003, in order to avoid the overhead catenary in the city with the maximum possible security. It utilizes a third rail buried between the main rails. This third rail is segmented in short sections which are independently fed. Hence, there is only electrical energy, when the tram is over those sections.

The problem of this system is the great difficulty of its control and installation, because of everything must be interconnected, in order to know which is the actual position of the tram in any moment. For this reason, it has a large cost, which is more than 2.5 times the catenary price.

Figure 3-17: APS. [30]

3.4.8 SCIE

SCIE (Sistema de captación inferior de energía from Spanish) system which was developed by Construcciones Auxiliares Ferrocarril (CAF), also uses a third rail as the APS. However, in this case this rail is only found in the stop.

It has a positioning and identification system and also a switching system, so that the rail only feed the train is parked on top of it (Fig. 3-18 shows an example).

The stop time (20 seconds) is used for charging the the accumulators ACR (Acumulador de carga rápida also from Spanish) installed in the train. ACR system was also developed by CAF with the *Greentech* brand, being based on supercapacitors (high-power density), Li-on (high-energy density) or a combination of both in hybrid systems as [29] shows.

Figure 3-18: SCIE [28].

The SCIE system is cheaper than APS, but its range is limited because of the ACR. It has already been installed in Zaragoza (Spain) and Luxembourg.

3.4.9 SCSE

SCSE (Sitema de captación superior de energía from Spanish) system has also developed by CAF, however in this case, there is not a buried rail, if not it hangs on top, but the positioning system is still needed, as well as the ACR system, according to internal documentation [28].

As the rail is not accessible for people, there is not need to have a great security level as SCIE. This make it a cheaper system, although the charging time is higher because the pantograph must up and down.

SCSE has already installed by CAF in Kaohsiung (Taiwan) and Seville (Spain).

Figure 3-19: SCSE [28].

3.4.10 Pantograph

Although this element belongs to the rolling stock, as it is the link between the train and the infrastructure, it will be briefly described. The pantograph (see Fig.3-20) is a device responsible for transmitting the electrical energy, which provides the traction force to the trains which have electrical machines as primary traction source. It is based on an articulated mechanism which is tasked with maintaining the friction plates in constant contact with the contact wire of the catenary. On which is located on the roof of the traction unit and is adjustable in height automatically.

Figure 3-20: Pantograph [32].

3.5 Energy distribution and Substations

3.5.1 Energy distribution

The energy distribution for railway applications follows the scheme of Fig. 3-21. As it can be seen, the energy is generated in the power plants (thermal power stations, hydraulic power stations or renewable energy plants) with a high-voltage level between 3-11 kV, where the voltage is boosted up to 400 kV for transporting with minimum power losses (at high powers, the higher the voltage, the lower the losses).

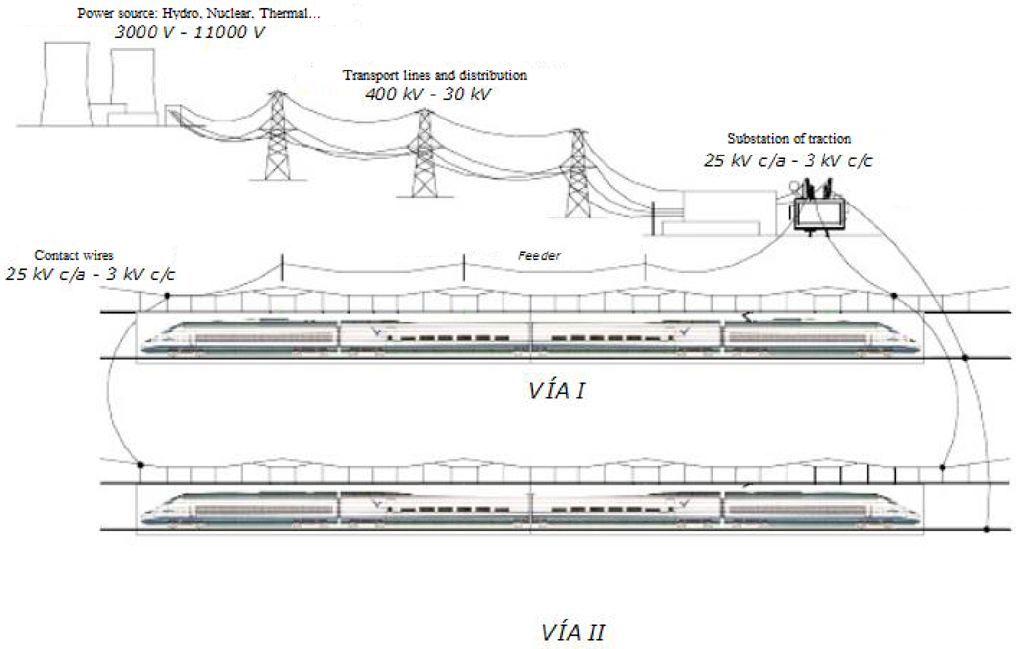


Figure 3-21: Generation, Transportation, distribution and consumption system [33].

Once the consumption point is near, the voltage is reduced to distribution level which is between 10-66 kV (this depends on the distribution company and geographical zone). Until here, the power flow is the same than for other loads.

In the traction substation, the energy must be transformed and rectified (this last one only in case of DC installations), in order to feed the catenaries and thereby to the trains.

3.5.2 DC Substations

In this subsection, a short description of the different parts of DC substations will be done, in order to understand in which parts it is divided by the time for sizing. Fig. 3-22 shows a simple example of the main different parts of these kinds of substations. Notice that all information regarding substations was extracted from [33].

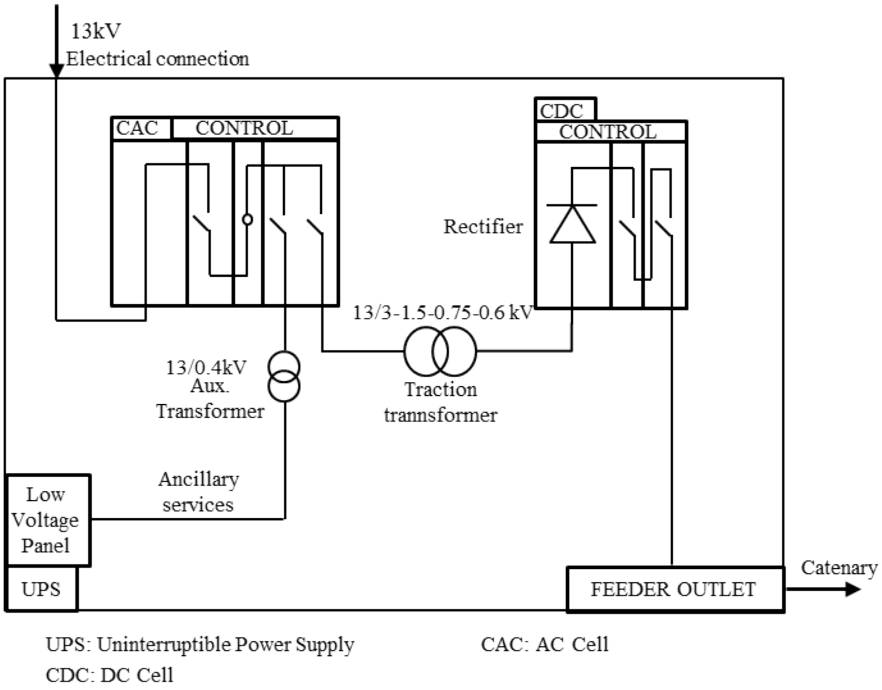


Figure 3-22: DC substation example.

Electrical connection

This is the cable entrance to the substation. These feeding lines can be overhead or underground lines, operating at high voltage.

In DC substations, the voltage level goes from 10 to 66 kV. However, in AC substations, this depends on the energy supplier. These electrical connections may be electrical company property, private ownership (as ADIF) or ring connection (to increase the availability) of the substation.

The typical devices these electrical connection have are:

- Disconnector.

- Automatic valves (only in overhead lines).

- Circuit breaker.

- Protection transformer and protection relay.

Measurement cell

The measurement cells is formed by an equipment set which evaluate the current and voltages by using current transformers, voltage transformers and the measurement equipment. They are usually done by using company measuring cells or also can be private ownership by the consumer, in order to know which is the consumption of that substation.

Rectifier sets

Rectifier set is understood as the set of equipment and cutting elements which handle to transform the input AC energy into a lower voltage-level which comes from the high voltage lines into DC current needed for the catenary and the trains.

These important elements in the DC substations are composed of:

- Isolators and circuit breakers.

- Transformer (800- 6600 kVA): Nowadays, the topology most used is the oil-filled transformers, because of the large amount of power they can manage. However, there are other installations which work with dry type transformers.

- Rectifier: It is used for transforming the AC current into DC current. In railway application, the nonreversible rectifiers (diode bridge), are the more used topology (robust and cheaper) because most of the substations are unidirectional, however there are also reversible substations which use bidirectional converters such as back-to-back converters (using IGBTs). Diode bridges are usually 6-pulses or 12-pulses, which are the normal converters.

- Smoothing inductor and harmonic filtering equipment: They are used for removing some harmonics and thus obtaining flatter voltage profile. The higher the number of pulses of the diode bridge, the less these filters are needed.

Feeder outlet

From the positive busbar of the rectifier set, it is defined a feeder outlet to the breaker and disconnector set, prior to the catenary start. They are composed by DC breakers, automatic valves, feeder disconnector and by-pass disconnectors.

Auxiliary services

The auxiliary services of a substation is the transformer and the general low voltage panel set which handle the power supply to all services of the installation in order to ensure its proper operation and the correct maintenance. In this board the typical protections are included (circuit breakers, transformers and disconnectors).

The services which are fed by this board are:

- Lighting.
- Ventilation and air conditioning.
- Control/ Communication and traffic signals.
- Battery/UPS.
- Tram stations.

Control

The control and command of all substation equipment is made by Programmable Logic Controllers (PLC), which govern each of the installation parts and then, sending or receiving through a communication network all needed signals to the PLC or to the local position in the substation. This is called distributed control.

There is a more conventional control way that is called ”conventional control” and is done by ADIF. In this kind of control, all signals and orders are wired to the remote telecontrol stations through contactors and relays.

Interlock

Interlock system of a substation is understood as the safety lock sets, electric locks sets, etc., and it is in charge of assuring that all outage and repositioning manoeuvres of voltage are done safely for both maintenance personnel and equipment.

Protective earth

The earthing network is the basic protection element of a substation. In here, all regulation from MIE RAT 13 [34] are applicable, therefore, both the AC equipment earths and the earths that make up the DC equipment must form a single circuit.

The earth network must be equipotential with the following earth circuits connected to it:

- Ground circuits coming from the building or outdoor AC park.
- Return circuits from the rails, monitored by current detection in installations with NONISOLATED rails.
- Ground circuit from DC.

Return

The return circuit, as it was aforesaid, it goes through the rails (normally), and then it is connected to the negative connection point of the rectifier. This connection can be done directly to that point or by using a negative well. The physical connection is done by pressure terminals or by exothermic welding.

3.6 Energy storage systems

In this section the different types of energy storage systems used in railway and even other transport systems will be reviewed.

3.6.1 On-board accumulators

On-board energy storage systems can store energy in different ways (electrically, chemically or mechanically), with a wide diversity in technologies such as supercapacitors, batteries, flywheels and fuel cells as [35] explains. These systems store and spend the energy on-board the vehicle, and then that energy is periodically renewed from wayside facilities (regenerative braking, battery chargers ...).

These system provides different performance depending on their SOC, in order to save life cycles, due to some of them have a limited lifetime. Furthermore, as the amount of stored energy within these devices is not infinite, any vehicle may be stranded with no power for any random reason (traffic congestion, delays ...).

In case of railway systems, eBuses and EV, only two OESS will be taken into account, as the supercapacitors and batteries, being the other technologies relegated for other applications.

Supercapacitors

Supercapacitors are devices with high efficiency and high power densities, which allows the fast charge and discharge without lost of efficiency, for thousands of cycles. These devices have been installed on different vehicle types by almost all major car builders as [35] indicates. The main purpose for using them has been for taking advantage of the regeneration energy of the vehicle (if there is not possibility to inject the energy into the grid), and thus reducing the energy consumption. However, nowadays they are more used for off-wire applications, where the vehicle must circulate with no grid-connection. In off-wire applications with this kind of OESS, they are in charge of injecting the necessary power to accelerate the train. Notice they are normally used in a hybrid manner.

Batteries

Batteries have been used as OESS since the beginning of horse-less operation in the mid-1800s as [35] explains. In fact, it is previous to the use of overhead contact wire. Batteries are the most widely used OESS in the world, since for example, are those we use as storage in our vehicles with the lead-acid batteries. They can be made from different compounds such as lead-acid, nickel iron, nickel-metal-hydride, lithium, etc.

As it is known, all types of batteries store chemical energy, being able to provide energy for several hours. Their energy density is higher than other OESS such as supercapacitors or flywheels, being one of the reasons why they are usually used in a hybrid manner with other technologies. For long distances in off-wire applications they are far superior to either supercapacitors and flywheels, however, their slow discharge rate usually results in a lower acceleration and overall performance, so for these cases, it is needed another device with a high power density.

3.6.2 Off-board accumulators

Off-board energy storage systems usually share the same technology concept than OESS, but in this case, these devices are located within the AC/DC substations. These devices are hardly used currently, however they are a clear alternative to the substation reversibility and a good way to provide voltage support to the DC traction system at certain instants as [36] explains.

Chapter 4

Simulation Programs

4.1 ITINER

Knowing the energy consumed by a train along each route is a very important aspect, especially in order to know which will be the cost of its life cycle. It is so important that it has become one of the main arguments in the sale of a railway, being increasingly frequent that customers include in their contracts contractual penalties for the breach of the consumptions indicated in the offer, which makes it fundamental to know and reduce the actual energy consumptions.

There are several initiatives for reducing the energy consumption of railways. Firstly, the direct consumption can be faced by reducing the weight or by using more optimized and efficient equipment. Once this is done, there is still room for improvements in different aspects, such as the driving management, generation of energy optimized routes or the optimal management of auxiliaries.

This was the main aim which motivated to CAF for developing ITINER. It is a simulation tool for simulating rail routes and computing the consumption of their rail vehicles. It allows generating train models and simulating their dynamic and electric behaviour for certain route in order to know the vehicle consumption in an accurate manner, by introducing the efficient driving strategies and fulfilling with the time requirements that the operator sets in certain infrastructures. It is a powerful application, in comparison with others of the same nature, because of the great amount of train parameters are introduced into the program. These simulations are independent from the feeding type, being indifferent if it is an AC or DC power supply.

The main feature of ITINER is that it is based on solving analytic equations, which allow to determine the needed time and space for pass from an initial speed to a final one that is also known. The calculation is done by the program by applying the maximum traction effort or brake available according to the performance of the vehicle. Notice that Appendix A shows a little tutorial for simulating a small tramway, so go there for more information. Any simulation is done by three steps:

4.1.1 Input data

The input data step is where all variables are assigned to the different input data, which some of them will depend on the kilometer (PK) of the route, introducing the characteristics of the vehicle to simulate, its route and the driving way. Al this information is introduced into the program by three excel files as [37] explains:

1. Simulation file: Here all information regarding the scenario to analyse, duration of the simulation is set, as well as the file names of the input data, and the file names of the output.

2. Route file: This file contains all information about the route (vertical and horizontal profiles, location of stations, speed limits, driving ways...).

3. Vehicle file: In this file, all general characteristics of the vehicle are set (weight, wheel radius, track gauge).

4.1.2 Simulation

In this process the speed profile is computed by the application. Here, several variables (driving way, electric brake, coasting) can be modified in order to fit the speed profile.

4.1.3 Post-processing

From obtaining the speed profile, the post-processing part is in charge of depicting the results in terms of time and speed, and also computing the consumptions and losses in the traction chain. Thus, obtaining the energy consumption of the train, which will be used for extracting the XTP (position-time-power) file for RailNEOS.

4.2 RailNEOS 2.0 Simulator

Sizing the electric railway systems requires several calculations before an adequate development due to the great amount of devices there are in these systems, and also to the very nature of the system, where the loads change their position in time. Because of this, CAF TE within the ESTEFI project, in collaboration to the University of Oviedo develops the RailNEOS tool, which is already in its second version. Thus, obtaining a powerful tool for simulating any railway system, achieving the more efficient installation as possible, and even introducing the new concept of mix-mode substations.

This software allows to CAF calculating the energy consumption from different substations within a certain trajectory, being able to see the voltage profile from the whole line, as well as different variables, such as active power, reactive power, currents, etc in a graphical environment. The energy consumption will be a key factor in order to obtain the more efficient installation as possible, as it was explained in the introduction chapter.

As starting point, a previous simulation based on rolling stock with the simulation program called ITINER must be carried out. As it was aforementioned, this program use the information of the train, from physical characteristic point of view (weight, wheel diameter, length of each car...) up to characteristics of the rails (alignment of the lanes, speed restrictions, crossings, curves, slopes, costs and spirals).

Once the rolling stock simulation of each train is done, an output file (txt file) is obtained, which is called XTP, whose results are introduced on RailNEOS as input, as well as the electrical infrastructure of the system, the different trajectories and the different operating schedules. Take into consideration there are other input files similar to XTP file, which include information of loads connected to nodes (TP) and even bus recharging points (XT), and that the load connected to nodes may be different EV charging points, or even lifts.

Starting from this information, any simulation on RailNEOS can be done by configuring the different parameters presented in 4.1. Look at the user manual of the application to see what means each configuration [38].

Table 4.1: RailNEOS configuration

Configuration	Base power definition S_{BASE}			
Base voltage	Base voltage definition V_{BASE}			
Node	AC disconnected	Ideal bidirectional	Deadband (DB) bidirectional	DB/nonDB unidirectional
Train	Configuration of different trains (η, traction curves..)			
Bus	Configuration of the different buses			
EES	On-board accumulators		Off-board accumators	
Lines	Train lines		Bus lines	
Links	Configuration of the different links			
Tracks	Train tracks		Bus tracks	
Profiles	XTP		XT	TP
Schedule	Train		Bus	Node

By configuring the parameters from Table 4.1, the electrical infrastructure of the railway system, the different routes are obtained and the schedule of each train, thus obtaining something similar to what Fig. 4-1 shows.

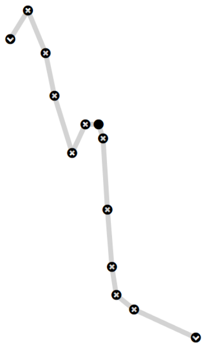


Figure 4-1: Simplified simulation scheme from the Vitoria tram.

The introduction of the different schedules for each train will generate the needed mesh for sizing or optimizing the infrastructure.

Once the different routes have been set, the departure times as well as the corresponding electrical infrastructure, the simulation can be carried out, obtaining results related to substations, rolling stock units or to various point of the infrastructure, such as intermediate nodes, links between different networks or storage systems.

Appendix B shows a little tutorial for simulating a small railway system, so go there for more information.

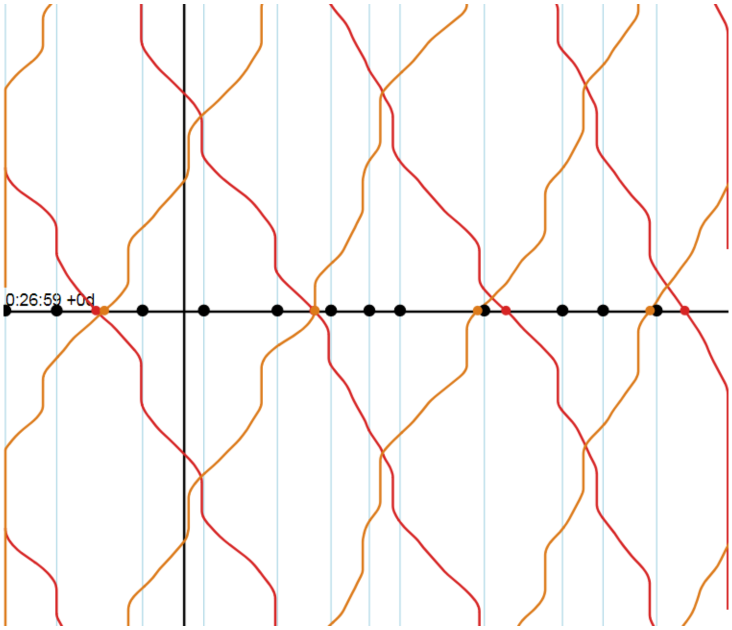


Figure 4-2: Mesh for the simplified simulation from the Vitoria tram.

Chapter 5

RailNeos 2.0 Validation

5.1 Introduction

In this chapter, the validation of RailNeos 2.0 will be carried out, which will be done by the simulation result comparisons between RailNeos 1.0 and RailNeos 2.0.

The simulated grid belongs to the suburban railway system from Málaga, on which connects three towns from the south of Spain (Alora-Málaga-Fuengirola). The information of this network is explained in Appendix B, whose parameters where provided by CAF TE.

This tool validation will be done by means of comparing, above all, the powers supplied and energy for each of the substations and explaining the reason for their differences. The results extracted from each train will also be analysed (by route and direction), where tensions and powers absorbed by each them will be compared. In this last case, only two trains for path will be studied.

For doing the comparison between both programs, the same grid must be simulated in both tools in order to extract the needed information, and then compare them in the same time step.

After the comparison, a small conclusions will be extracted, on which can be extrapolated to other simple cases as this one.

5.2 Validation: Trains

For the validation of the trains, a comparison between the output data from both programs will be done, only taking into account the most relevant information of the trains. These data are the catenary power and the train voltage. Because of the great similarity among the output data from the trains of all routes (Fuengirola-Málaga-Fuengirola and Alora-Málaga-Alora), only one train of each route will be analysed in this paper.

Fig. 5-1 shows the catenary power which is absorbed by the trains in the simulation of both simulators and also the power deviation in percentage of RailNeos 2.0 respect to RailNeos 1.0. As it can be seen, the differences between them are negligible, due to their values varies as much a 0.000006 %, which is nothing. This great similarity is because of the information introduced in the program is the same, or what is the same, that the trains are defined by the same XTP file and the line impedance, substation powers, schedule and the others grid parameters are equal.

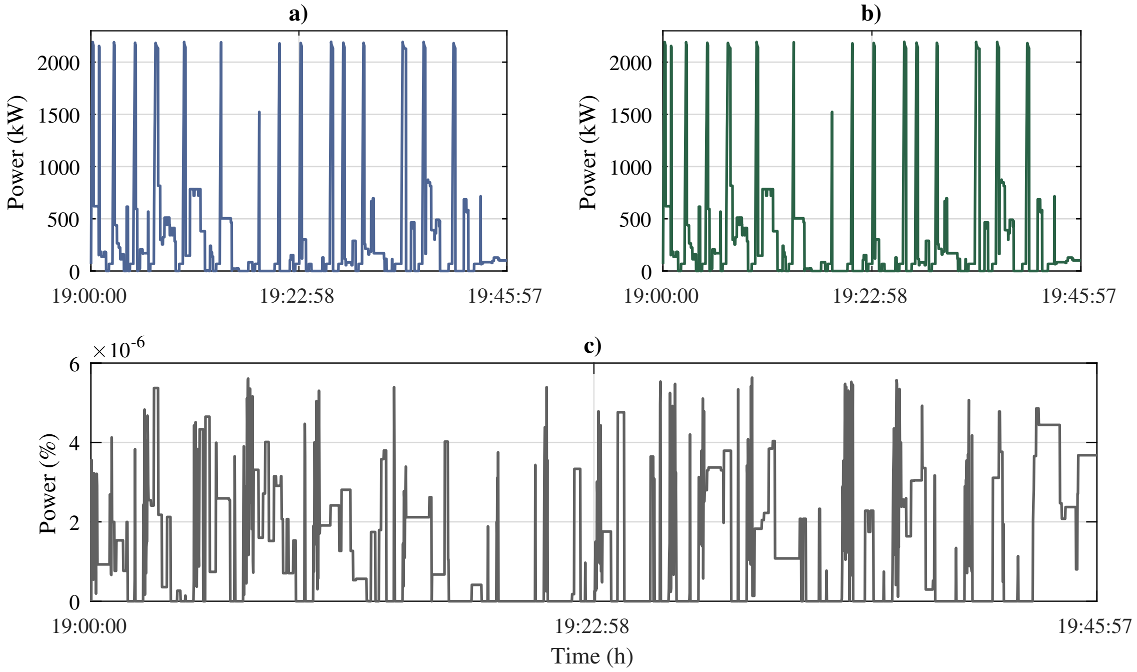


Figure 5-1: Train 1: a) Catenary power in RailNeos 1.0. b) Catenary power in RailNeos 2.0. c) Power comparison in percentage.

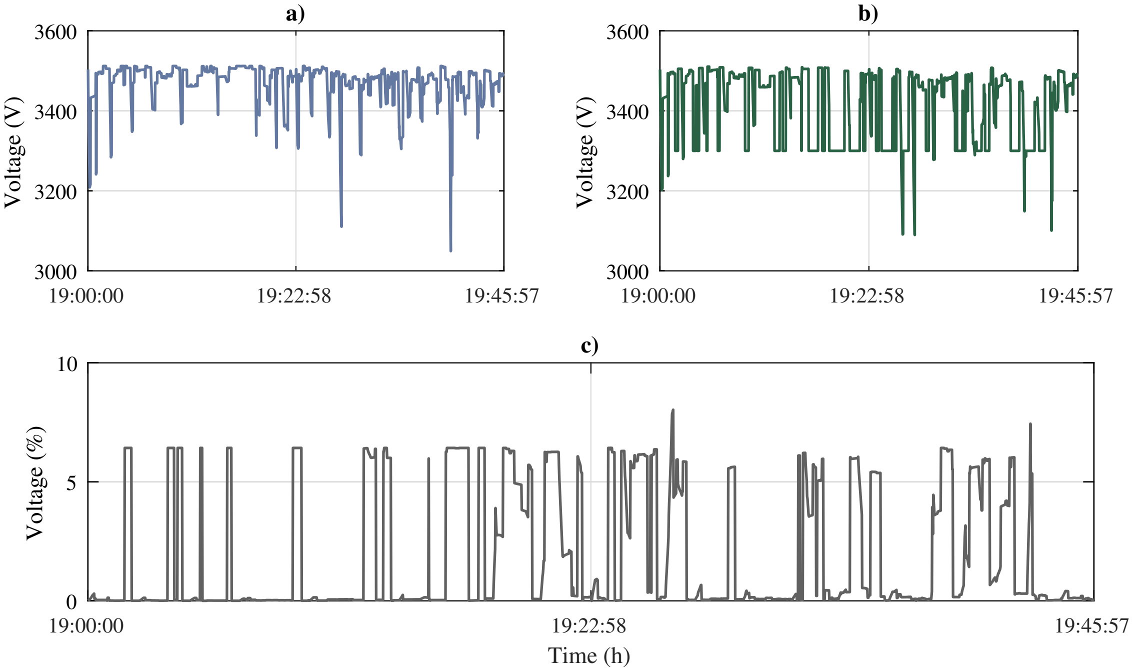


Figure 5-2: Train 1: a) Catenary voltage in RailNeos 1.0. b) Catenary voltage in RailNeos 2.0. c) Voltage comparison in percentage.

On the contrary, the same cannot be said of the voltage profile of the trains, which is depicted in Fig. 5-2. As it can be seen, the voltage profiles are quite similar when there are power consumption by the train; nevertheless during the cases where there is not power consumption, they are not solved by none simulator, so each one imposes a predefined voltage in these cases. In case of RailNeos 1.0, the open circuit voltage is used (3512 V), and in RailNeos 2.0 uses the rated voltage (3300 V). In these events the voltage variation peaks appears, as Fig. 5-2 c) shows, obtaining peaks which reach 6.5 %. Another reason for these voltage variations of the simulator is the difference of currents in the lines, because of the power provided by one simulator and the other can vary, due to RailNeos 1.0 does not take into account losses at substation level. This will be explained below.

The same occurs in the other route (Alora-Málaga), where the power and voltage variation are shown in Fig. 5-3 and Fig. 5-4. Therefore identical conclusions can be extracted.

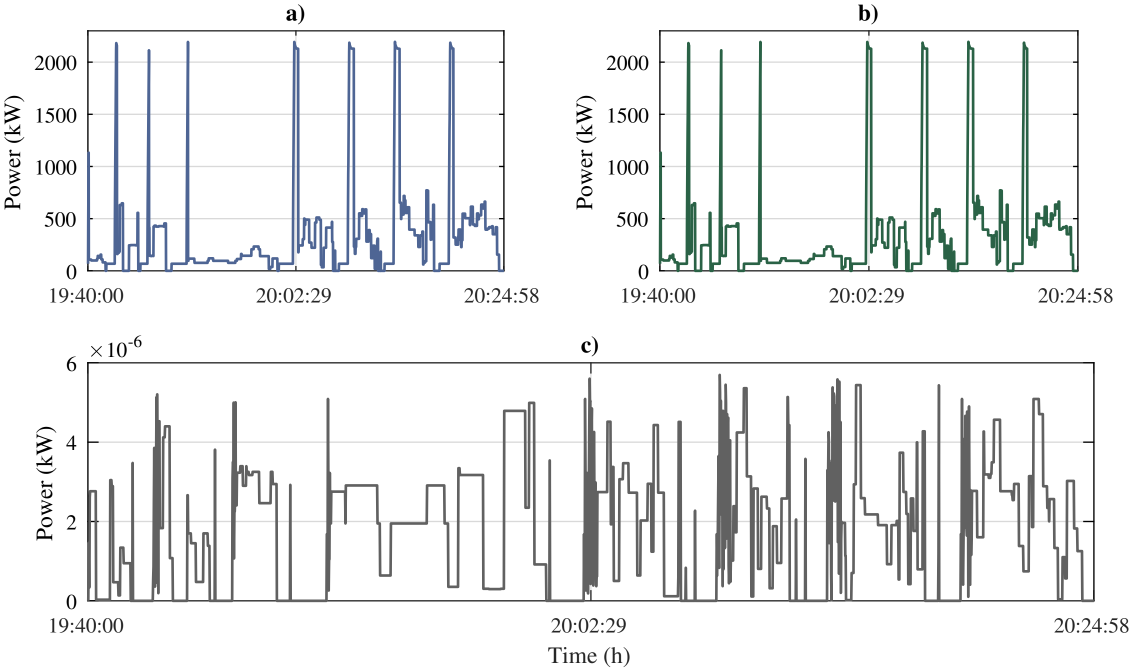


Figure 5-3: Train 13: a) Catenary power in RailNeos 1.0. b) Catenary power in RailNeos 2.0. c) Power comparison in percentage.

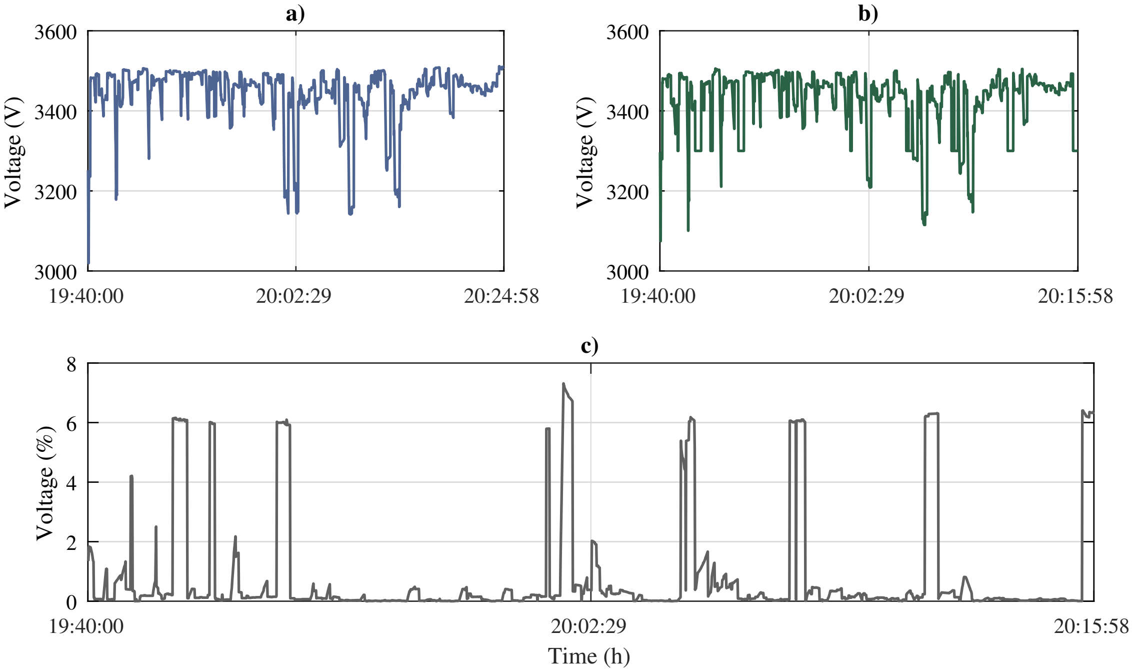


Figure 5-4: Train 14: a) Catenary voltage in RailNeos 1.0. b) Catenary voltage in RailNeos 2.0. c) Voltage comparison in percentage.

5.3 Validation: Substations

Once the information of trains from both simulators has been analysed and validated, its the turn of the substations. For this has been done a validation at global level, where the total provided power by all substations, as well as the total energy are compared, seeing thus the differences between simulations. Also more local validation has been done in energy terms, where the difference of the energy evolution of each substation is observed.

5.3.1 Global analysis of the substations

Fig. 5-5 shows the power profile of how each simulator computes the power provided by each substation. As it can be seen the power provided by RailNeos 1.0 is rougher, going from 0 to P$_{subs}$. On the other hand, the RailNeos 2.0 power evolution is smoother, being the power supplied by each substation in cases of train power equal to zero, close to zero but never reaching this value. However, the energy provided by each of them (the area), is practically the same.

This difference at time to calculate the power will cause small differences in power and energy, as it will be seen below.

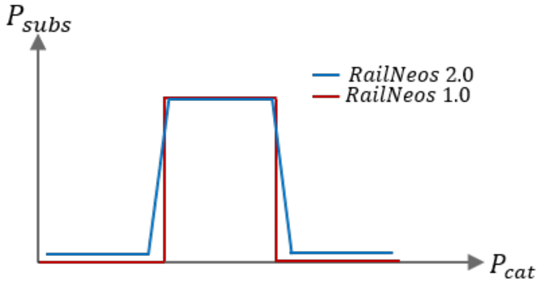


Figure 5-5: Power of substation in RailNeos 1.0 and RailNeos 2.0.

Fig. 5-6 shows the total power deviation in percentage of RailNeos 2.0 respect to RailNeos 1.0. As it can be seen the differences are minimum, around 0.01 %, during most of the time; nevertheless there are certain instants where these values reach 6 %. This differences are caused by the differences between the solver algorithm of both programs. Because of the complexity of the RailNeos 1.0's railway system model, and its computation difficulty, some simplifications were introduced in the system, in order to obtain consistent results, within a reasonable time.

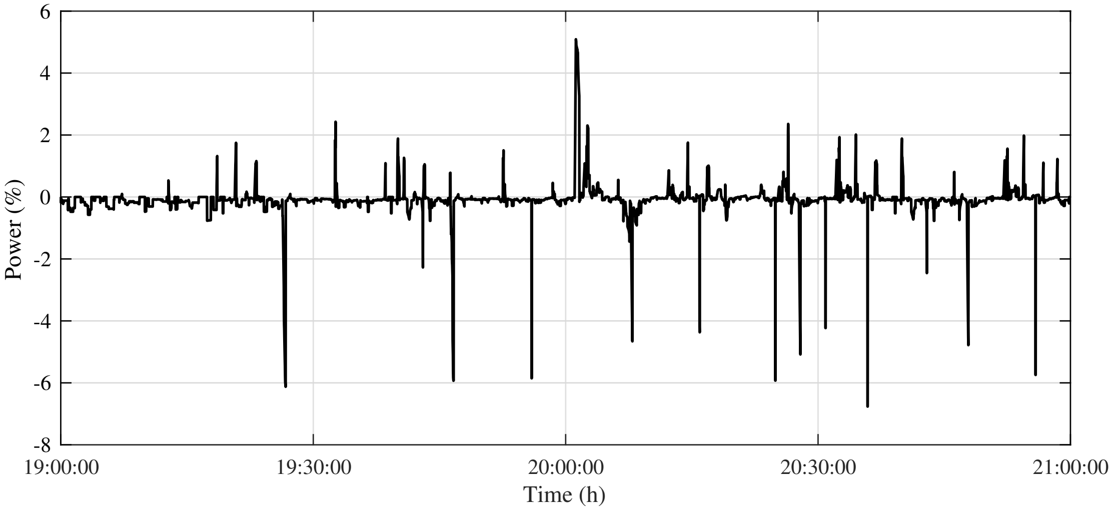


Figure 5-6: Total power percentage of all system between RailNeos 1.0 and RailNeos 2.0 simulation.

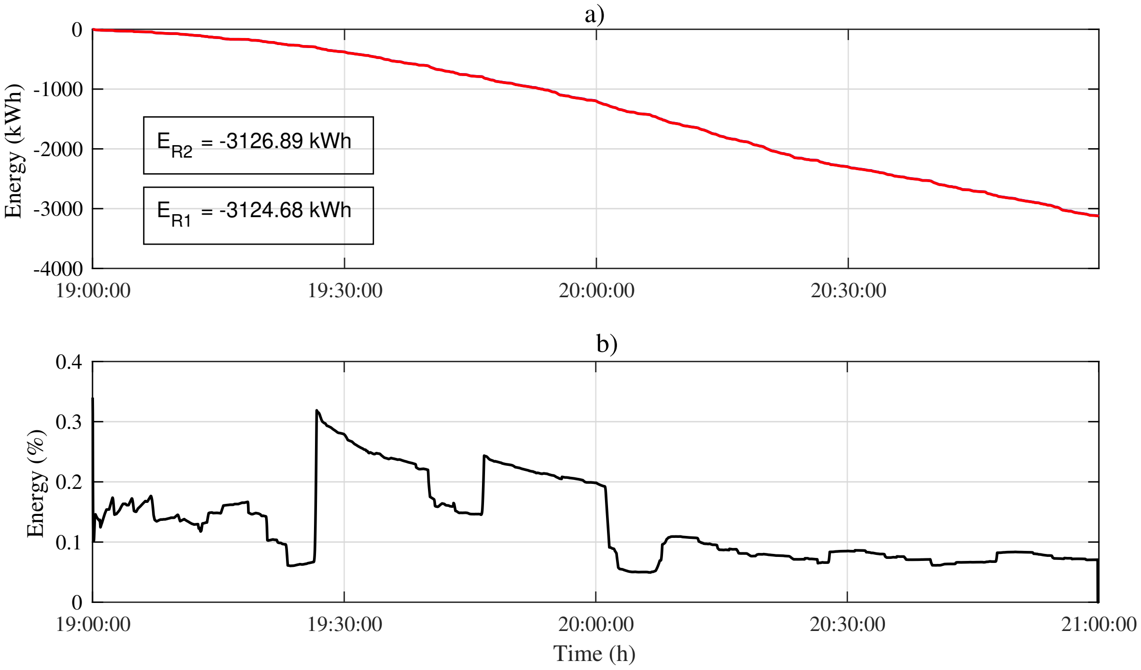


Figure 5-7: a) Energy evolution of all substations in RailNeos 1.0 and RailNeos 2.0. b) Energy difference between both simulators.

These simplifications are based in the losses calculation of the substations, where although there is an internal impedance where there is a voltage drop through it, there is not losses in it, due to it was decided to neglect them, by equalling the ac power and the dc power. As it can be seen, the selected solution works fine in most of the times, but not always, because of the system is not completely correct. In case of RailNeos 2.0, the losses in the substations were taken into account, therefore it presents more real results.

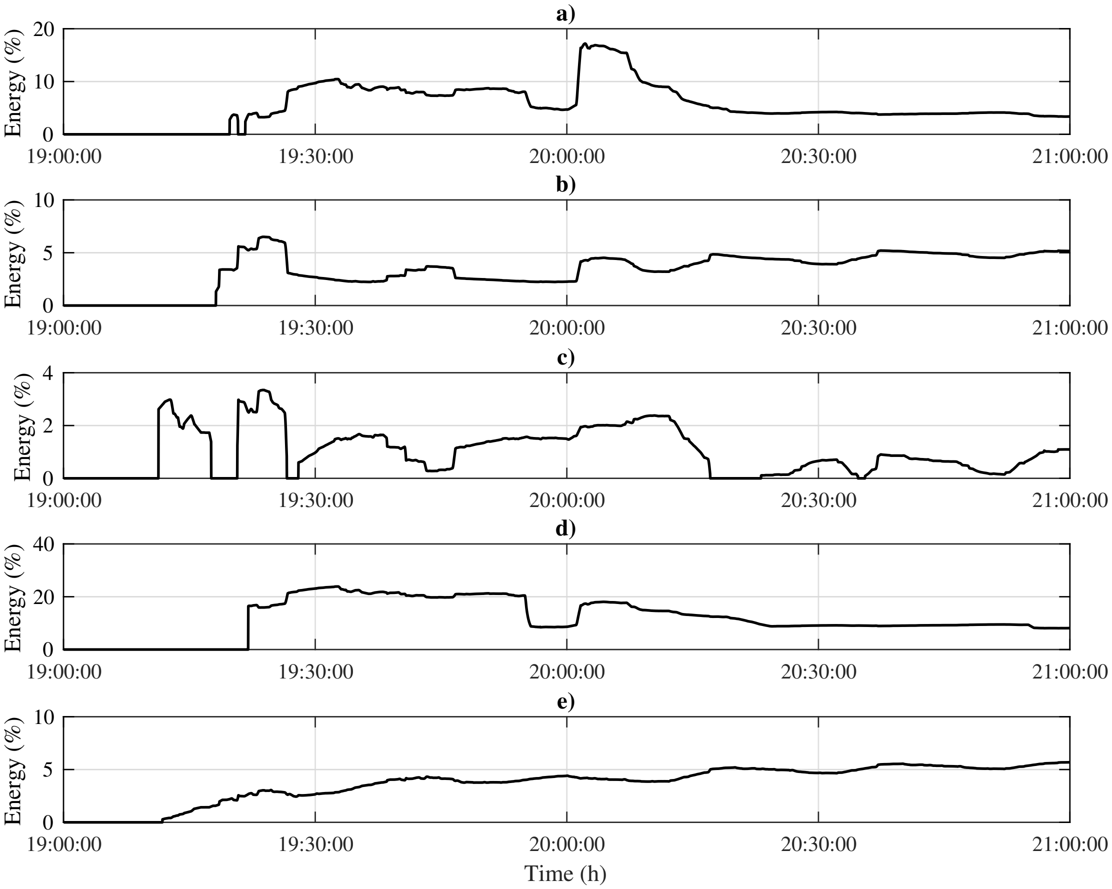


Figure 5-8: a) Percentage of difference energy results of the "Pizarra" substation between RailNeos 1.0 and RailNeos 2.0. b) Percentage of difference energy results of the "Los Prados" substation between RailNeos 1.0 and RailNeos 2.0. c) Percentage of difference energy results of the "La Comba" substation between RailNeos 1.0 and RailNeos 2.0. d) Percentage of difference energy results of the "El Chorro" substation between RailNeos 1.0 and RailNeos 2.0. a) Percentage of difference energy results of the "Carvajal" substation between RailNeos 1.0 and RailNeos 2.0.

As it can be seen in Fig. 5-7, where the evolution of the energy in both simulators (a) and the energy deviation in percentage of RailNeos 2.0 respect to RailNeos 1.0

(b), there is not so many differences, because of these small variations appear in a few instants. Hence the final energy consumption is the same, and variation between simulations, does not exceeds the 0.3 %.

5.3.2 Local analysis of the substations

In this subsection, a small analysis of the energy deviation between both simulators of each subsection will be done.

This variation is shown in Fig. 5-8. These deviations present hight values in general, this is because of the comparison between energies, which have small values cause high differences, over all in substations which provides little power (such as El Chorro, Pizarra). Notice that the energy deviation which is zero at the beginning of each plot of the figure, are because of this reason, which causes too high values which do not represent anything (above all at the start of the simulation). However this is not the only reason, because as it was explained in the previous subsection, there are small variations between simulators due to the the absence of losses in RailNeos 1.0.

5.4 Conclusion

In this chapter the validation of a real railway system has been used for validating the RailNeos 2.0 simulator. In this validation the used data have been the train voltages and their powers, as well as the total power and energy provided by the substations.

From this result comparison, it can be concluded tat there are not big differences at global level (energy and power terms), but at a local level, due to the simplification of the original simulator (lossless substations), the current through the lines and the voltage vary.

In the case of RailNeos 2.0, this does not occur, because it includes all electrical calculations. The other differences are not appreciable.

Chapter 6

Analysis of a Real Railway System

6.1 Introduction

In this chapter, a detailed analysis of a real railway system located in Málaga will be done, in which is a suburban system which connects three Spanish towns, such as Málaga-Fuengirola" and "Málaga-Alora". All the information regarding this network has been provided by the CAF TE staff in order to perform a simulation in RailNeos 2.0.

This analysis will serve to understand better how railway systems work, taking into account their main variables, such as voltage and power for later perform a detailed energy study during a simulation of two hours. This study will be used for testing the simulator, and thus seeing that the results make sense.

The previous explanation belongs to the base case of the chapter. However after that, some modifications will be done in order to test different scenarios. First of all the ON-board accumulation will be tested, in order to explain how it works, and then seeing how the system behaves with these devices. Then, the same will be done with the Off-board accumulator.

Finally, another variation of the base case in terms of train frequency will be studied, but only taking into account the energy that is managed for the system, in order to extract some conclusions.

6.2 Base case: Málaga suburban system

In this section, the suburban system of Málaga will be analysed. Notice that all information of this network is in Appendix B, where how to simulate this grid in RailNeos 2.0 is explained.

6.2.1 Simple case: one train

First, let's start for one of the easiest analysis of the system, which is related with the voltage and power of a train. As it can be seen in Fig. 6-1, where the voltage and power of very first train of the system are depicted. As it can be seen, at the instants where the train demands power to the system (positive power), on which the train is accelerating, the voltage of the system drops (as in any other power system), because it demands current.

On the other hand, when the train brakes, it injects energy to the system, causing that the catenary voltage increases, as if the catenary was the load and the train a current source.

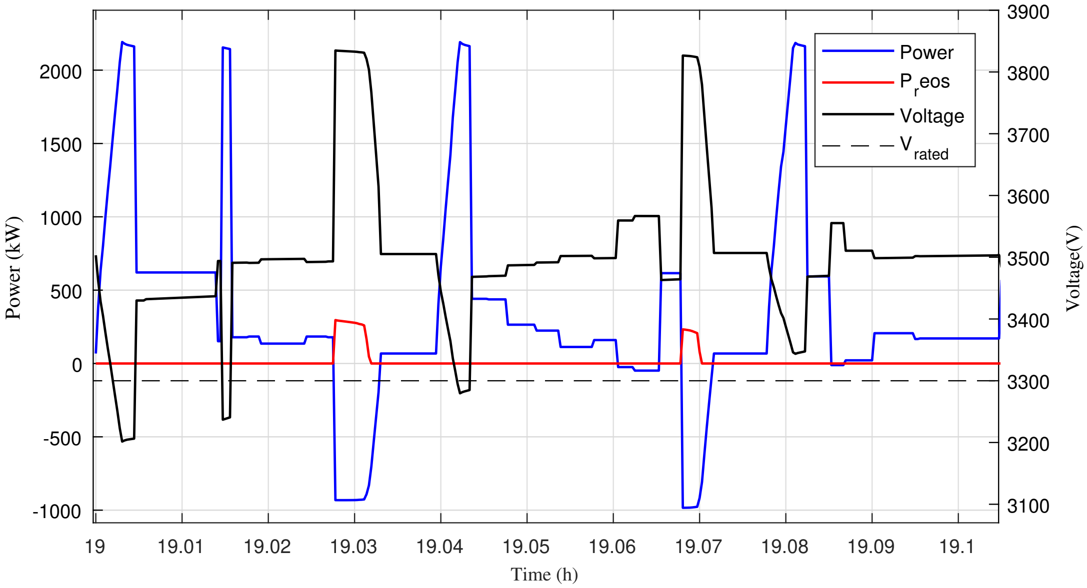


Figure 6-1: Voltage and power of a train when it accelerates or decelerates.

In Fig.6-1 the burned energy in the rheostat of the train (in terms of power) is also depicted. This power arises when the train is braking and the catenary cannot absorb more power because its voltage is so high. In case of any simulation, the cases where this power can appear are modelled with the curve that 6-2 depicts. In real life it is managed by a control system.

For this simulation when the voltage is between 1.15 and 1.2 pu, part of the power will be burned in the braking rheostat, and the other injected into catenary. If the voltage is higher than 1.2 pu, all regenerative power will be burned int the braking resistors.

There are another region in the curve, which is the not supplied power region. The trains are in this region when the voltage is too low, hence the current are enormous. It is a method to auto-protect itself from this type of overcurrents. The problem is that when the train is in this region, the power of the train will be reduced and being able to even stop in the middle of a journey. Notice that each train has its own curve.

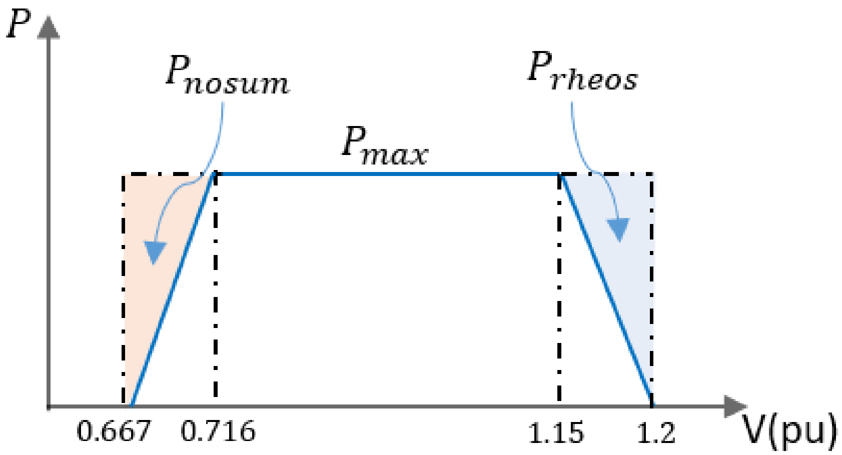


Figure 6-2: Curve of a train (P-V).

In case of this railway system there are not supplied power, because the grid is well dimensioned, but each time the voltage is higher then 3795 V, energy will be burned in the braking resistor.

In order to understand better, similar cases of accelerating and braking cases will be analysed in an instant of the simulation, in terms of voltage and current.

Accelerating case

In this first case, a scenario where only one train is accelerating will be analysed through the voltage and power profile. In this instant the train is absorbing 2176.64 kW. As it can be seen in Fig. 6-3, this power is absorbed by Train 0.0, and the "Carvajal" substation supplies most of the energy. However, "La Comba" and "Los Prados" also provides energy, although almost negligible in comparison to the others. Take into account that all power profiles follow the next feature. They are positive when the energy go from left to right, and it is negative on the other way around.

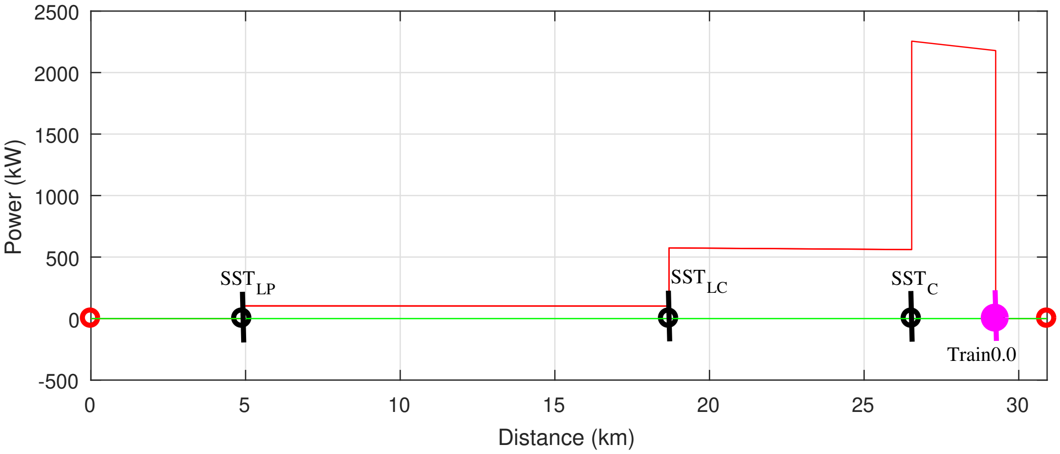


Figure 6-3: Power profile when only one train accelerates.

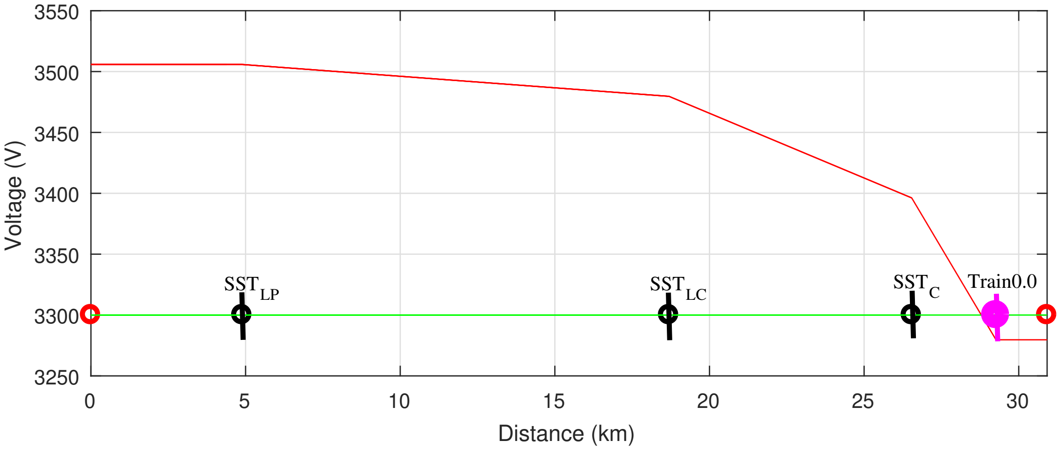


Figure 6-4: Voltage profile when only one train accelerates.

This situation also can be analysed from the voltage profile point of view (see Fig.

6-4). Looking at the figure, the great voltage drop indicates the position of a train with a great consumption of power.

Also the voltage drop caused by the energy which goes from "La Comba" to "Carvajal" and from "Los Prados" to "La Comba" can be seen. In case of the station there are not voltage drop, because they are disconnected to ac side, therefore they do not inject energy (zero current).

Braking case

The other study case is where the same train brakes in a regenerative manner, on which will inject power to grid. In the selected instant of this simulation, the train injects -1173.83 kW, as the power profile depicted in Fig. 6-5 shows. As there in only one train and "La Comba" substation is bidirectional, all energy goes towards it. The other substations are blocked.

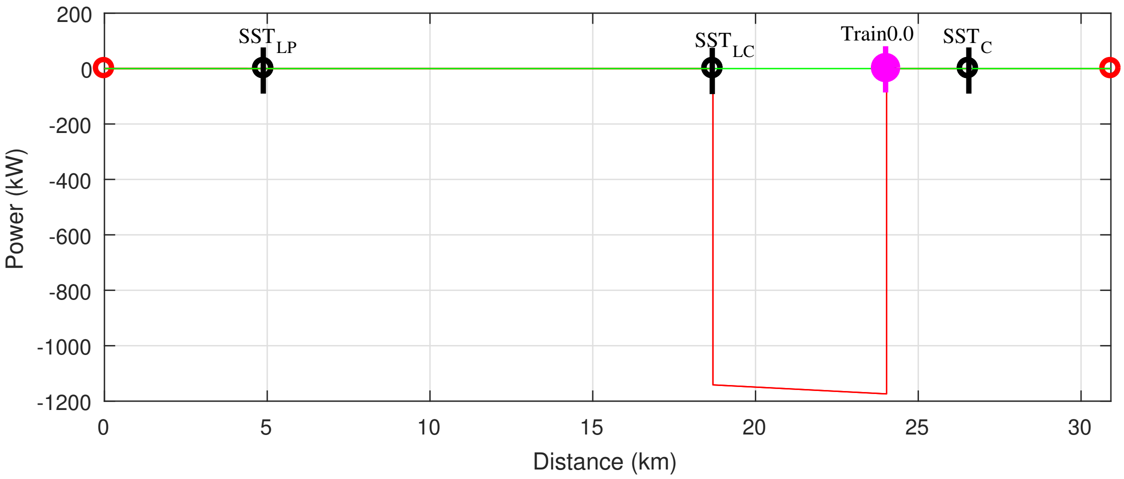


Figure 6-5: Power profile when only one train is braking.

It also can be seen from the voltage profile point of view that Fig. 6-6 shows, where there is a voltage drop towards "La Comba". Notice that in this case, as the voltage at the train is higher than 3795 V, a small amount of energy is burned in the braking resistors (48.05 kW).

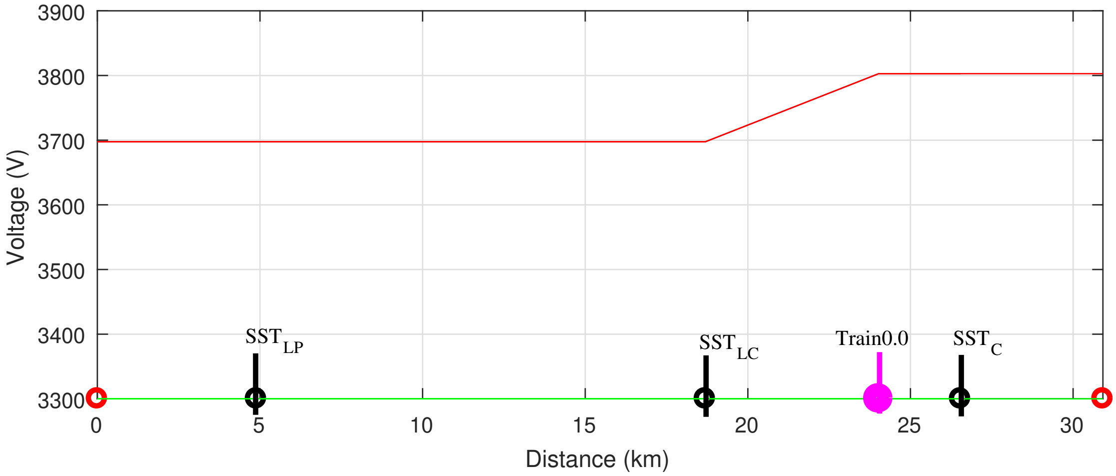


Figure 6-6: Voltage profile when only one train is braking.

6.2.2 Multi-train case

Once the simple cases are analysed, more complex cases will be discussed. Each of them will belong to a different route. One for the route Málaga-Fuengirola and the another one for Málaga-Alora.

Route Málaga-Fuengirola

The following study case, will be analysed at an specific instant where there are four trains circulating at the same time. Fig. 6-7 shows the power and voltage of each train around an instant, on which is 19:33:05 in the simulation. As it can be seen some trains are consuming and others generating.

The powers consumed or generated by each train can be checked in Table 6.1. They will be used below to check that the calculations of the simulator are consistent. This table also shows the power flow of each substation, the initial value is the power that leave the substation/node and the final power and the final value is the power that enters in the next node (being the difference the losses in that stretch).

As in the case of only one train in the system, this multiple-train case will be analysed with the power and voltage profiles.

In order to analyse this case, Fig. 6-8 and Fig. 6-9 will be used, where the power profile and voltage profile of this instant are depicted, respectively. In both figures, all trains along the route can be seen in their current positions. Note that the magenta trains go in the Fuengirola-Malaga direction, and the blue ones go from Málaga to Fuengirola, being the red point on the left, Málaga and the right one Fuengirola.

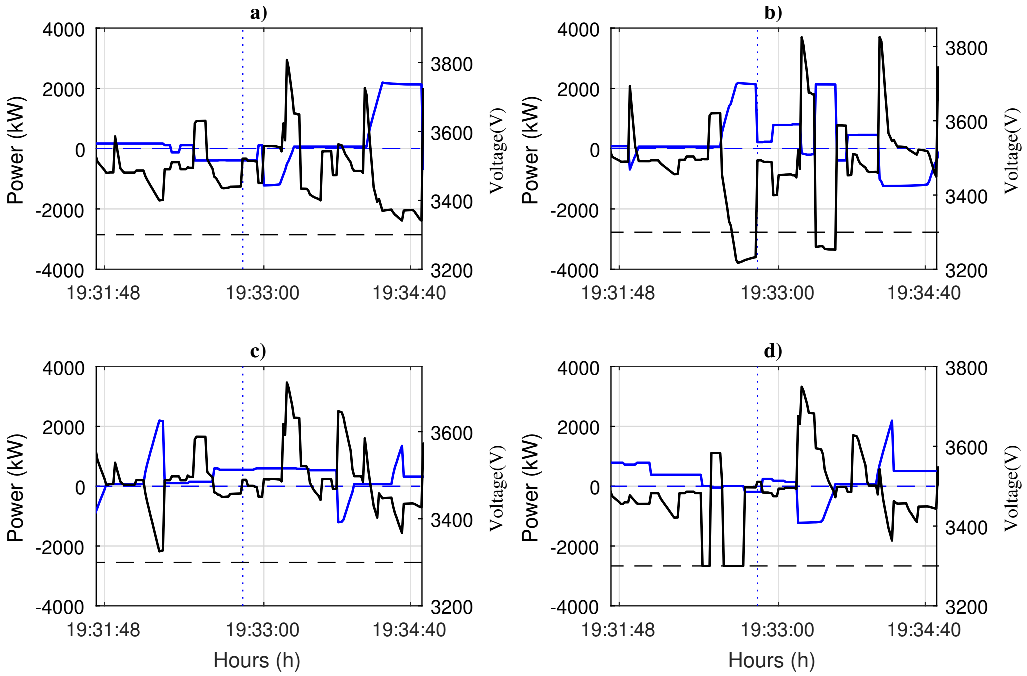


Figure 6-7: a) Voltage and Power curves of the Train 0.0. b) Voltage and Power curves of the Train 1.1. c) Voltage and Power curves of the Train 1.0. d)Voltage and Power curves of the Train 0.1.

In the power profile, the direction of the power can be observed, seeing how the Train 1.1 is consuming a great amount of power, and it is feed by "Los Prados" substation, and by the energy that Train0.0 is inyecting into grid. On the other side, in case of Train 1.0, it is absorbing power because the train is accelerating, being this fed by " La Comba" substation, "Carvajal" substation and also the regenerative power that Train0.1 injects.

The voltage profile (see Fig. 6-9) shows something similar than the power profile, but in terms of voltage drop, being able to show us where the maximum consumption is, and also the direction of the energy. Furthermore, both figures shows the stations that are blocked, because of the current is zero.

Once the spatial distribution of power and voltage is analysed, a kind of "kirchhoff current's law" (KCL), but in terms of powers will be used, in order to verify that all cases are correct. In this case, only the dynamic nodes (trains) will be analysed. It will be assumed that if they are correct, the substations are correct too.

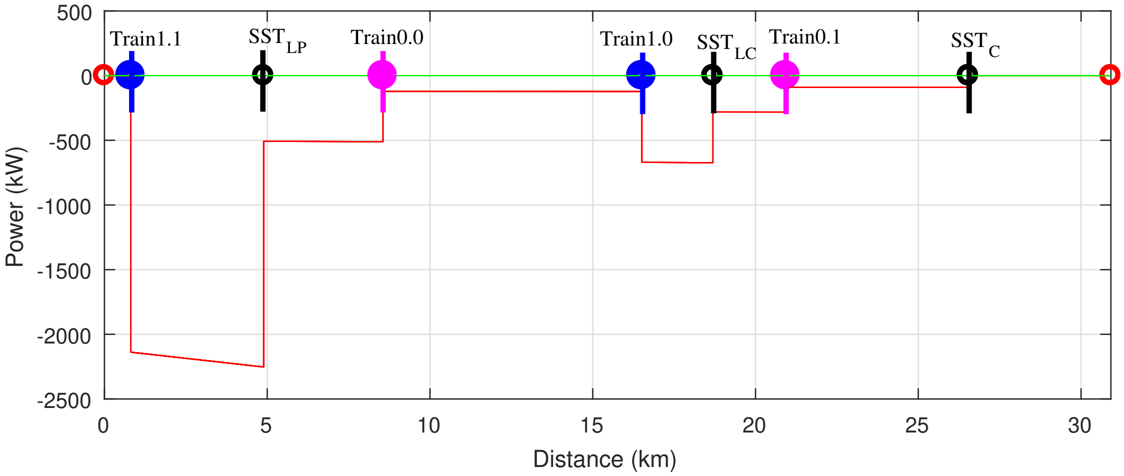


Figure 6-8: Power profile at 19:33:05, when four trains are circulating in Málaga-Fuengirola route.

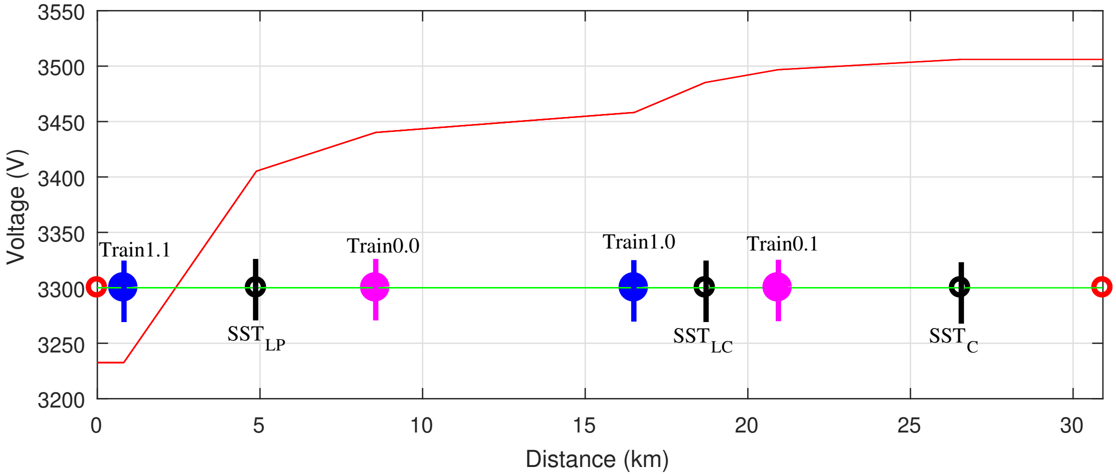


Figure 6-9: Voltage profile at 19:33:05, when four trains are circulating in Málaga-Fuengirola route.

Fig. 6-10 shows the injected and consumed power in the dynamic nodes. These can be checked by a simple calculation, on which are done in equation 6.1.

As it can be seen, KCL in terms of power can validate the results, being the addition of the injected powers equal to almost zero. These small differences are negligible, due to they are in the worst case of only 100 Watts.

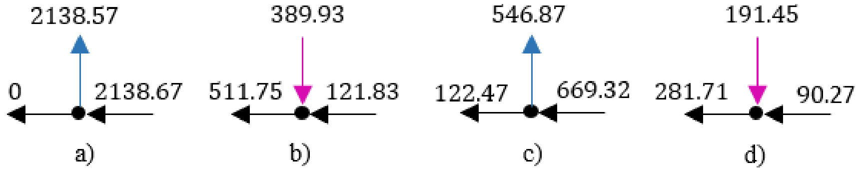


Figure 6-10: a) "KCL" with powers in Train 1.1 node. b) "KCL" with powers in Train 0.0 node. c) "KCL" with powers in Train 1.0 node. d) "KCL" with powers in Train 0.1 node.

Table 6.1: Power injected/absorbed by substations and trains in Málaga-Fuengirola route

From	To	Initial/Final Value [kW]
Málaga	Train 1.1	0/0
Train 1.1	SST$_{LP}$	2138.67/2252.67
SST$_{LP}$	Train 0.0	506.56/511.75
Train 0.0	Train 1.0	121.832/122.47
Train 1.0	SST$_{LC}$	669.32/674.555
SST$_{LC}$	Train 0.1	280.78/281.71
Train 0.1	SST$_C$	90.27/90.51
SST$_C$	Fuengirola	0/0

Train	Power [kW]
Train 0.0	-389.93
Train 0.1	-191.45
Train 1.0	546.87
Train 1.1	2138.57

$$
\begin{aligned}
&Train1.1 \rightarrow 2138.67 - 2138.57 + 0 = 0.1kW \\
&Train0.0 \rightarrow 511.75 - 121.83 - 389.93 = 0.01kW \\
&Train1.0 \rightarrow 122.47 + 546.87 - 669.32 = 0.02kW \\
&Train0.1 \rightarrow 281.71 - 191.45 - 90.27 = 0.01kW
\end{aligned}
\tag{6.1}
$$

Route Málaga-Alora

The case that will be discussed belongs to a specific instant where there are two trains circulating at the same time in the Málaga-Alora route. As previous cases, the power and voltage of each train have been extracted and plotted in Fig. 6-11, being the specific instant 20:09:18. In this case, one train (Train 2.0) is accelerating/ absorbing power and the another one (Train 3.0) is braking/injecting.

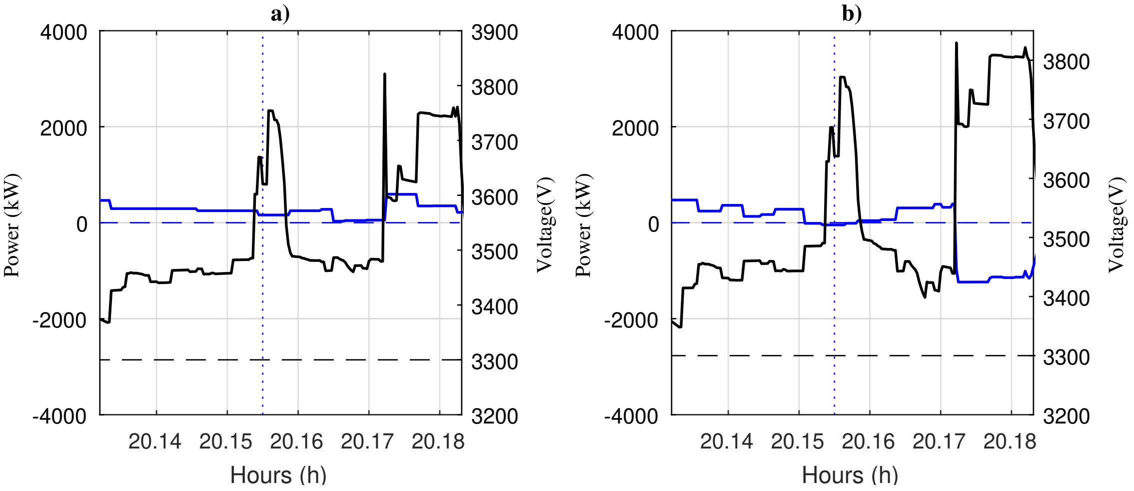


Figure 6-11: a) Voltage and Power curves of Train 2.0. b) Voltage and power curves of Train 3.0.

Table 6.2 has all the information about the train consumptions as in the previous case. They will be used for validating the calculations of the simulation as before, taking into account the power delivered or absorbed by train/substation. Note the configuration of the table is the same than in the previous case.

As in the case of only one train in the system, this multiple-train case will be analysed with the power and voltage profiles.

Using the power and voltage profile that Fig. 6-12 and Fig. 6-13 shows respectively, many information of the system in that instant can be extracted. Note that in this route, the yellow trains go in the Málaga-Alora direction, and the green ones go from Alora to Málaga. In this case the red point of the left is Málaga and the right one is Alora.

In the power profile, the direction of the power can be observed, seeing how the Train 1.1 is consuming a great amount of power, and it is feed by "Los Prados" substation, and by the energy that Train 0.0 is inyecting into grid. On the other side, in case of Train 1.0, it is absorbing power because the train is accelerating, being this fed by " La Comba" substation, "Carvajal" substation and also the regenerative power that Train 0.1 injects.

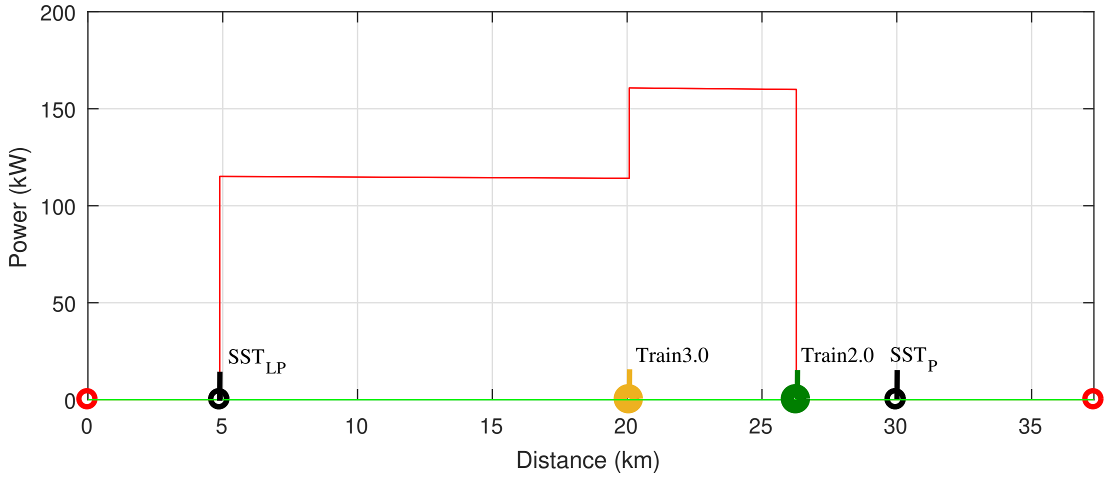


Figure 6-12: Power profile at 20:09:18, when four trains are circulating in Málaga-Fuengirola route.

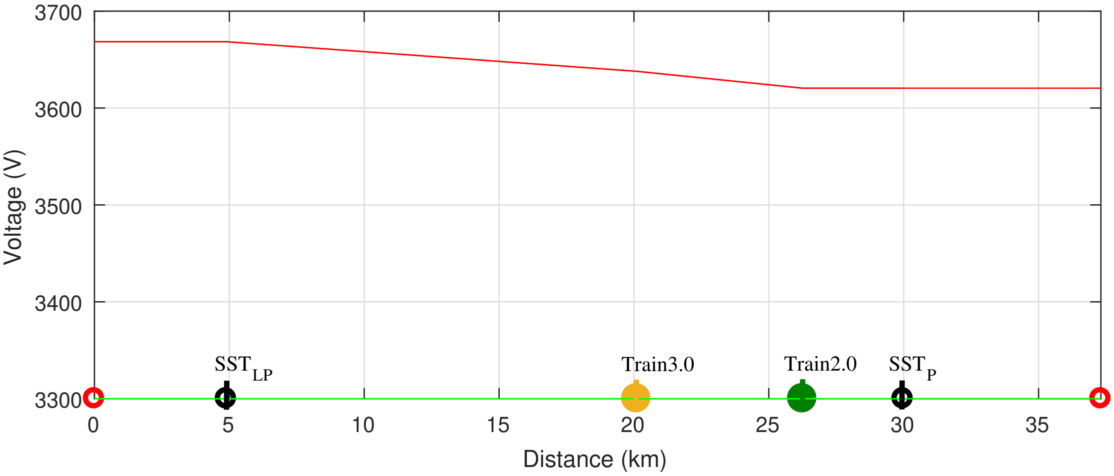


Figure 6-13: Voltage profile at 20:09:18, when four trains are circulating in Málaga-Fuengirola route.

The power profile of the route shows how ”Los Prados” is the only substation which is supplying energy, in which along with the energy that Train 3.0 is injecting, both feed Train 2.0. In case of the voltage profile, the voltage drop which the power injection of the substation and the train and its transmission can be seen. Note that in this case, there is a blocked substation (”Pizarra” substation).

Table 6.2: Power injected/absorbed by substations and trains in Málaga-Alora route

From	To	Initial/Final Value [kW]
Málaga	SST_{LP}	0/0
SST_{LP}	Train 3.0	-115.107/-114.148
Train 3.0	Train 2.0	-160.716/-159.95
Train 2.0	SST_{P}	0/0
SST_{P}	Alora	0/0

Train	Power [kW]
Train 3.0	-46.57
Train 2,0	159.93

After analysing the spatial distribution of power and voltage, let's discussed the validity of the results in this instant as in the previous case. For simplicity, the calculation will be done in a graphical manner as the previous case (see Fig. 6-14)

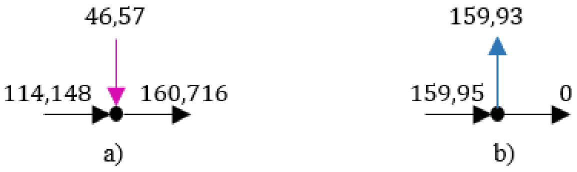


Figure 6-14: a) "KCL" with powers in Train 3.0 node. b) "KCL" with powers in Train 2.0 node.

In the same manner than the previous case, the dynamic node of each train will be analysed using the information of the previous figure or the table (see equation 6.2).

$$\begin{aligned} Train3.0 &\rightarrow 114.148 + 46.57 - 160.716 = 0.002kW \\ Train2.0 &\rightarrow 159.95 - 159.93 + 0 = 0.02kW \end{aligned} \tag{6.2}$$

In this case the results presents a lower error, with a maximum value of 20 Watts, in which is negligible.

Voltage evolution

Within the same case, seeing the voltage evolution makes sense, on which can be seen in Fig. 6-15, where the voltage evolution of each substation over the total simulation time are depicted.

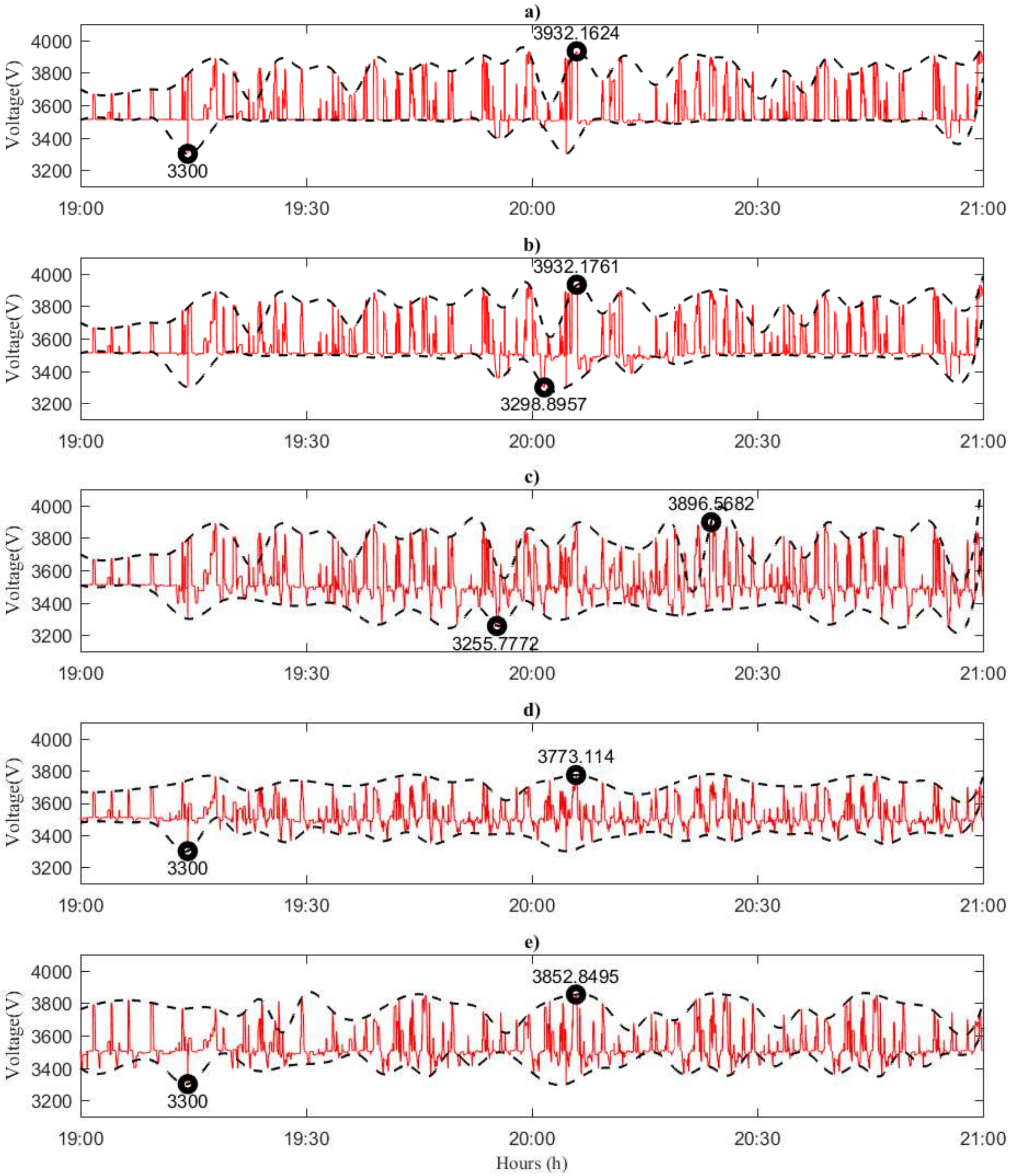


Figure 6-15: a) Voltage at EL Chorro substation along the simulation. b) Voltage at Pizarra substation along the simulation. c) Voltage at Los Prados substation along the simulation. d) Voltage at La Comba substation along the simulation. e) Voltage at Carvajal substation along the simulation.

As it can be seen the voltage varies depending on the power of the trains. For instance at the very beginning of the simulation the voltage of each substation is quite regular, because there is only one train. However, as the simulation progresses, the voltage variations become more abrupt. This is because there are several trains operating at the same time, where some of them are consuming and other injecting into catenary. Note that c) which is Los Prados substation, the voltage variation is the biggest. This is because of this substation belongs to both routes, and it must feed to many trains at the same time. On the other hand, La Comba substation has the smallest voltage variation. This is because it does not allow increasing the voltage when a train brakes, if not, the energy will be absorbed by it.

6.2.3 Energy study

For the energy study, different variables will be studied, such as the power of each substation, taking into account the power that is absorbed from AC grid and the power that is injected into catenary, in order to calculate thus, an estimation of the efficiency of the power converters. Besides the energy losses in catenary during the simulation will be discussed and finally the energy losses in the braking resistor.

Power converter losses

There are small power losses in the rectifier or inverters (if any). In Fig. 6-16, the power injected or absorbed (before and after the rectifier) for each substation can be seen, where as b) shows, there is a small difference between them. This difference can be seen better in c) where the power difference of each substation is depicted. Note that as it was known, there is a reversible substation (La Comba), which is the only one that injects power into the AC grid, and the other are unidirectionals.

Table 6.3 shows the average power of each converter side, as well as the average losses and the efficiency of each of them. As it can be seen, the nonreversible substations have the highest efficiency, being the reversible one, the less efficient. This is because the converter topology, where the switching losses of the transistor penalize to the bidirectional one.

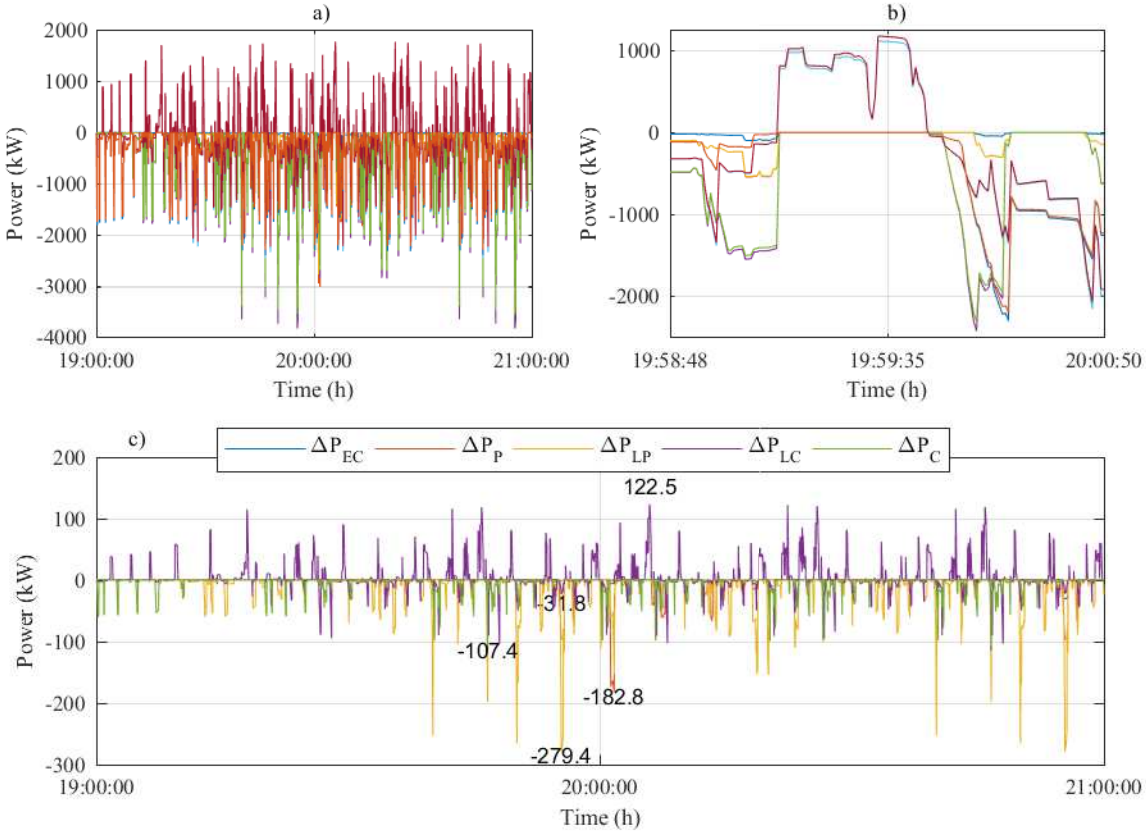


Figure 6-16: a) Power of each substation in AC and DC side. b) Zoom of the first figure. c) Power losses at each instant in the converters

Table 6.3: Average power of each side of the converter and efficiency of each converter

Substation	P$_{AC}$ [kW]	P$_{DC}$ [kW]	P$_{Loss}$ [kW]	η [%]
El Chorro	-28.73	-28.346	4.75	98.66
Pizarra	-132.973	-130.36	2.645	98.04
Los Prados	-440.618	-429.02	11.5933	97.37
La Comba	-157.68	-145.32	1.9888	98.17
Carvajal	-287.93	-283.18	4.7502	98.35

A similar conclusion can be extracted from the following figures, where Fig. 6-17 shows the energy evolution from the AC side point of view, and Fig. 6-18 shows the energy evolution of the power losses in each substation.

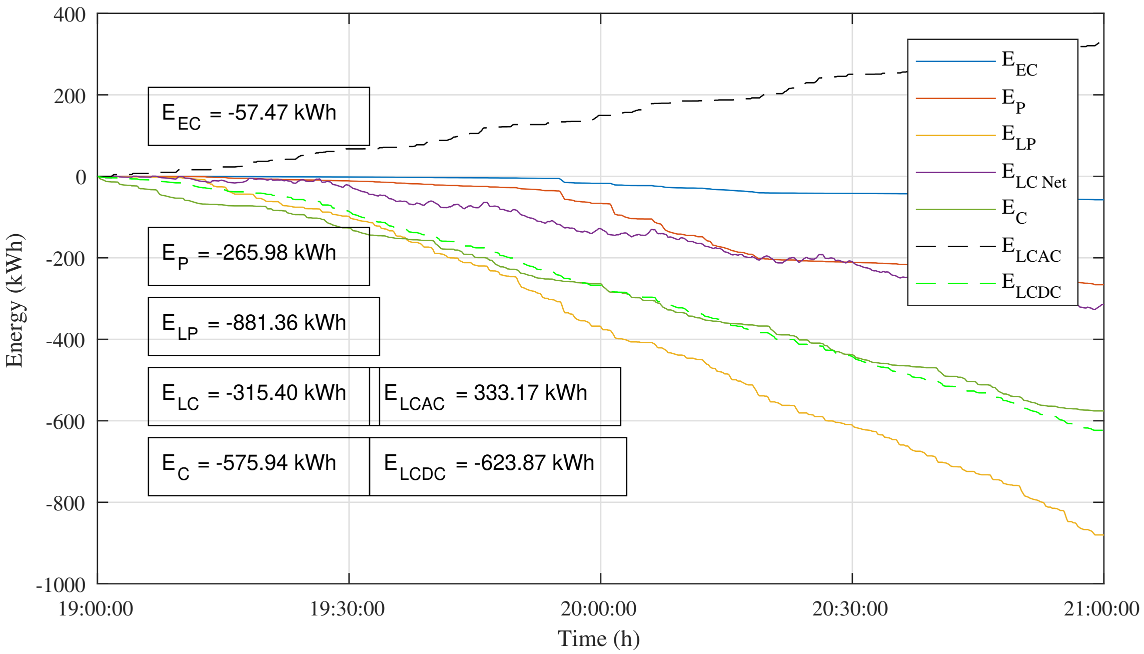


Figure 6-17: Energy evolution of each substation, with their final energy value.

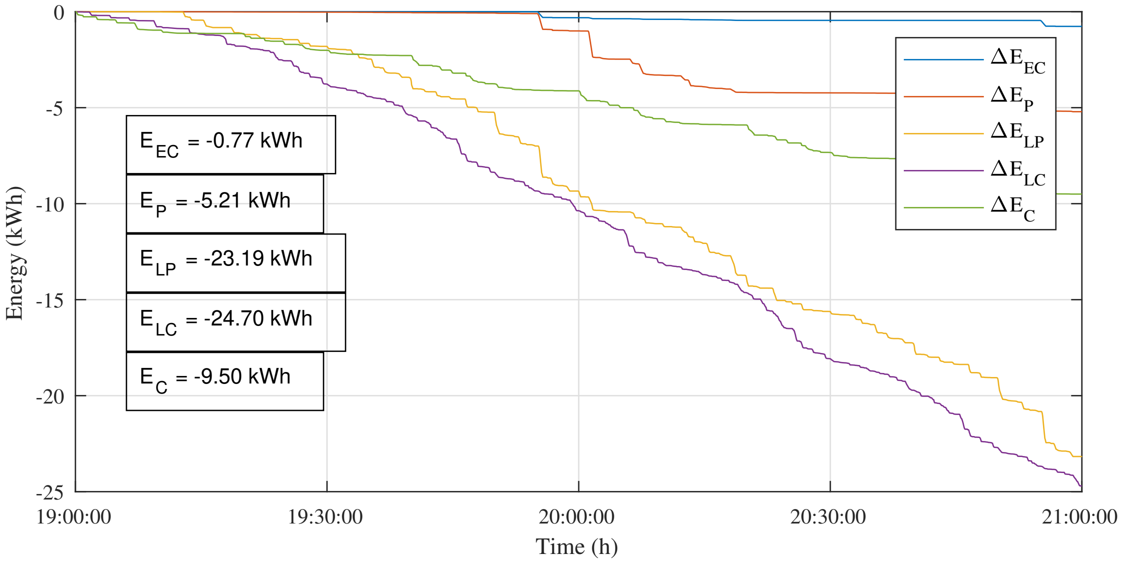


Figure 6-18: Energy evolution of the losses of each substation, with their final energy value.

The energy evolution of each substation shows many information of how the railway system is configured. Starting from the very first substation (El Chorro), in which do not belong to any route of the simulation, but it is electrically connected to the system. As it can be seen it hardly provides energy to the system (in comparison to the other substations). In case of Pizarra, it provides more power than the previous one, but pretty less than the others, because of during the simulation, only four trains circulate in its route.

Los Prados is the substation which feeds more energy to the system, because it is interconnected to both routes. Carvajal provides energy over all to the trains which leave from Fuengirola.

Finally, the most interesting of them is La Comba, which is the reversible substation. As it can be seen in the figure, La Comba does not inject so many energy in absolute terms, but this is because it injects part of the regenerative power into the AC system again, returning a total of 333.17 kWh.

Note that the net energy of La Comba is the addition of the absorbed energy to grid, the injected energy into the catenary plus the energy losses.

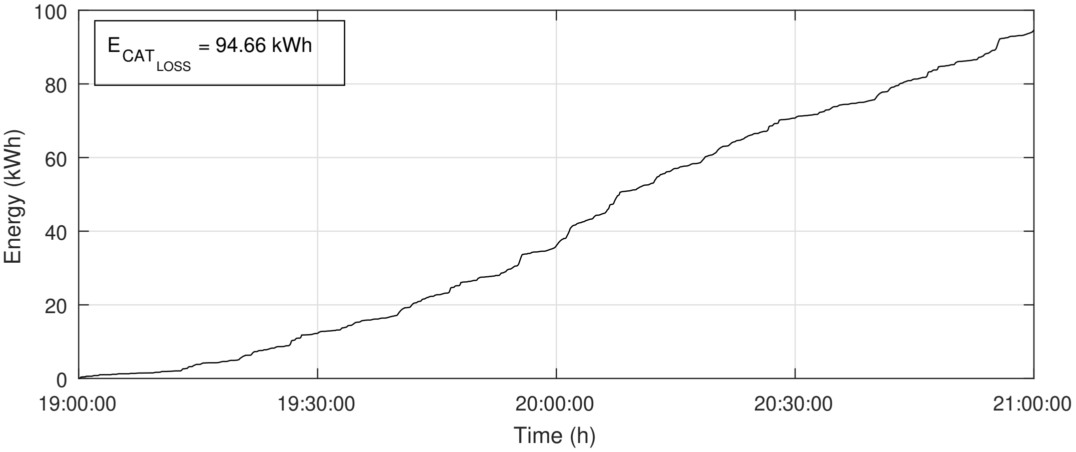


Figure 6-19: Power losses evolution in catenary.

Catenary losses

Another important point in the energy analysis is the losses in the catenary, because of the power is injected into the system from the substation, or from the trains where there is regenerative braking. However this energy is not consumed at the same point where it is produced, if not that it is transmitted along the lines. Due to the existence of a resistive part in the lines, in which will provoke voltage drops and energy losses, on which will be higher the higher the temperature and train traffic. In the case of this railway network, the catenary losses evolution in time is shown in Fig. 6-19, with a total energy losses of 94.66 kWh.

Train losses due to braking resistor

A similar analysis can be done with the energy losses in the braking resistor. In order to do it, the burned energy evolution in those rheostats has been depicted in Fig. 6-20. Where the addition of the total energy of each train leads to the total burned energy that can be seen in e), with a total value of 133.13 kWh.

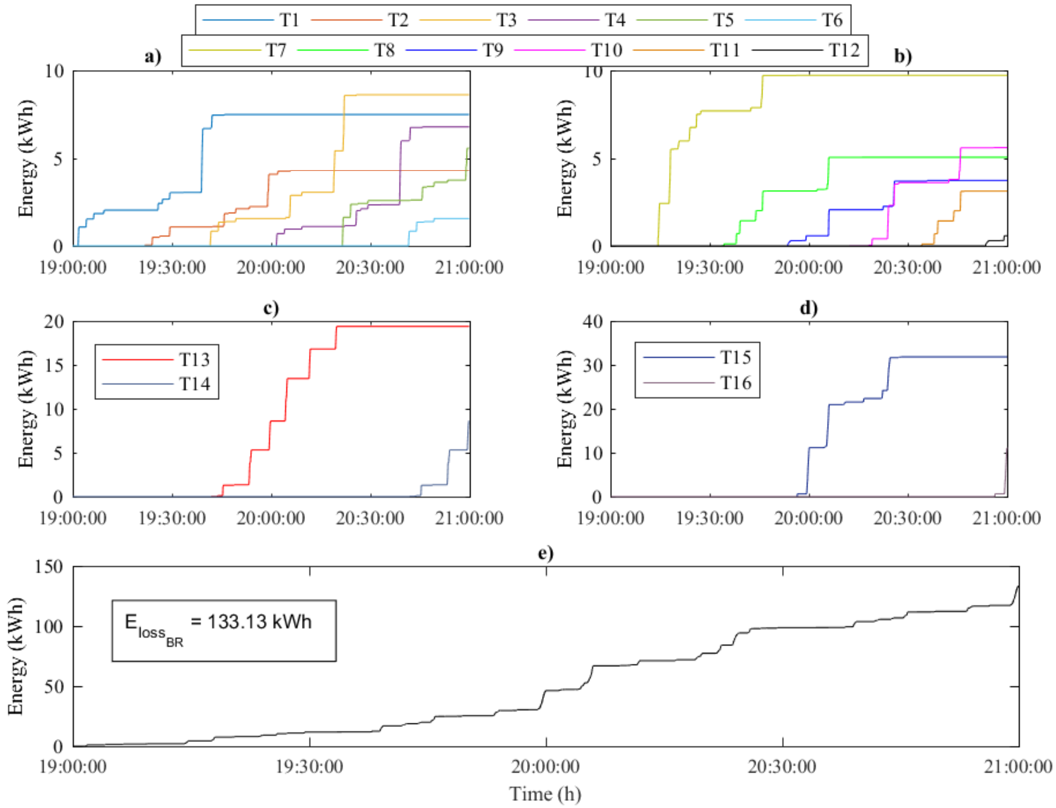


Figure 6-20: a) Energy loss evolution in rheostats for Fuengirola-Málaga route. b) Energy loss evolution in rheostats for Málaga-Fuengirola route. c) Energy loss evolution in rheostats for Alora-Málaga route. d) Energy loss evolution in rheostats for Málaga-Alora route. e) Total energy loss evolution in rheostats in two hours of simulation.

6.3 More Scenarios

In this section some modifications of the base case will be done in order to test different elements of the railway system.

6.3.1 Scenario: On-board accumulation systems

In this scenario, OESS have been included in each train of the system, in order to recover the regenerated energy and use it in the train itself, either for traction or auxiliary services. The intention of this scenario is explain how OESS work, and how they affect to the system. The accumulators that were used have a total capacity of 22 kWh. Note this scenario is only for educational aims, because of currently OESS are not used in suburban trains. Normally, they are used in trams with no-catenary stretches.

How OESS work?

As [38] explains, OESS are defined with a similar curve to the train curve, but in this case abscissas are the State of Charge (SOC) of the battery, and ordinates are the power the device can absorb or inject (see Fig.6-21). These devices, when they are in the lower SOC-range (between SOC1 and SOC2), they cannot extract all demanded power, being zero the extracted power when SOC is lower than SOC1. In case of being in the upper SOC range (SOC3 and SOC4), the operation is the same, but in terms of absorbing power from the train when it brakes. If SOC were greater than SOC4, the absorption of power is completely stopped in order to not overcharge the accumulator. Note that this definition a simple way to model the real behaviour of these systems.

Fig. 6-22 shows ten minutes of simulation, where the catenary voltage, the demanded power by the train, the power of the on-board accumulator and its SOC are depicted. Note that only one train is circulating at this moment, in order to see better how it works.

As it can be seen, the OESS starts with 50% of SOC, but as soon the train demands

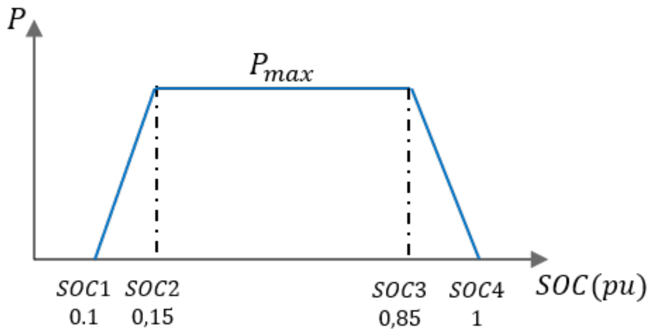


Figure 6-21: Model of the On-board energy storage systems.

power (P_{cat}), the ESS provides the needed power (P_{accu}) up to be discharged to SOC1, after that moment, all power is provided by catenary.

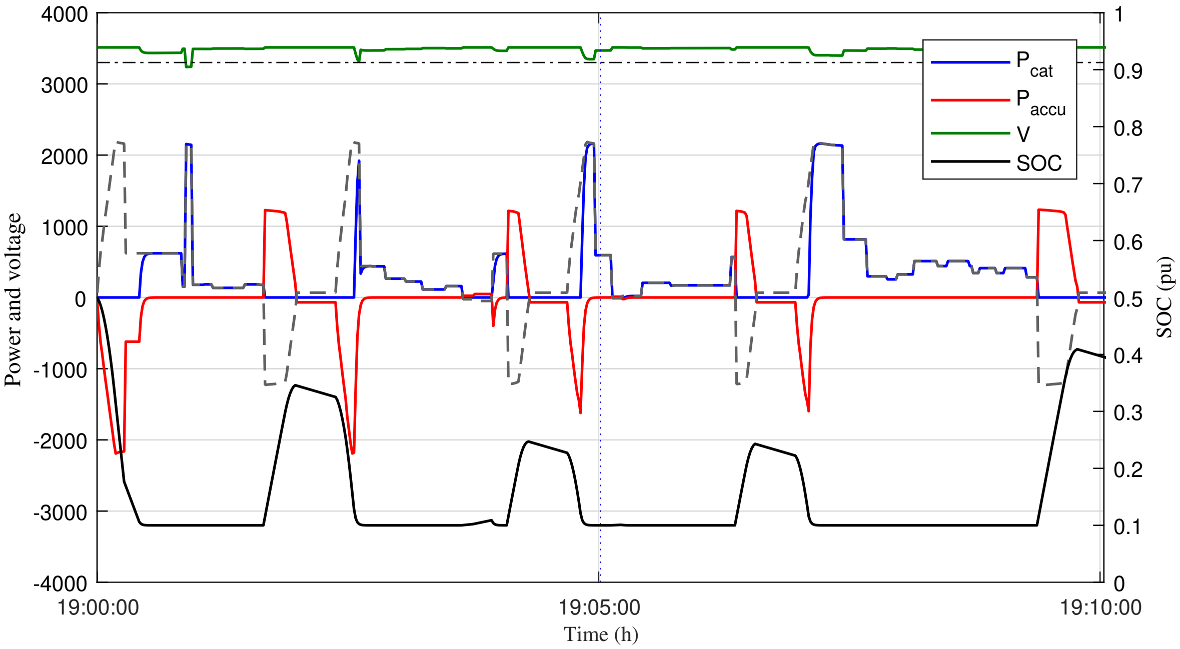


Figure 6-22: First ten minutes of simulation with only one train.

On the other hand, when the train brakes, the ESS starts to be charged at the same ratio that the train generates (this depends on the accumulator capabilities, in case of this simulation all generated power can be absorbed by the OESS). When the train stops braking, the battery charge stops and then it is discharge when there is again a power demand.

As it can be seen, the voltage variation are not so big, because of during many instants the power is provided by the OESS. This means that the variations of voltage in each substation are smaller, and as there is not high voltage levels, there are not energy losses in the braking resistors. This voltage variation of each substation can be seen in Fig. 6-23, where the evolution of each substation are depicted.

As it can be seen, none substation exceeds the open-circuit voltage, because each time a train brakes, this energy goes directly to the OESS (no energy injection into catenary).

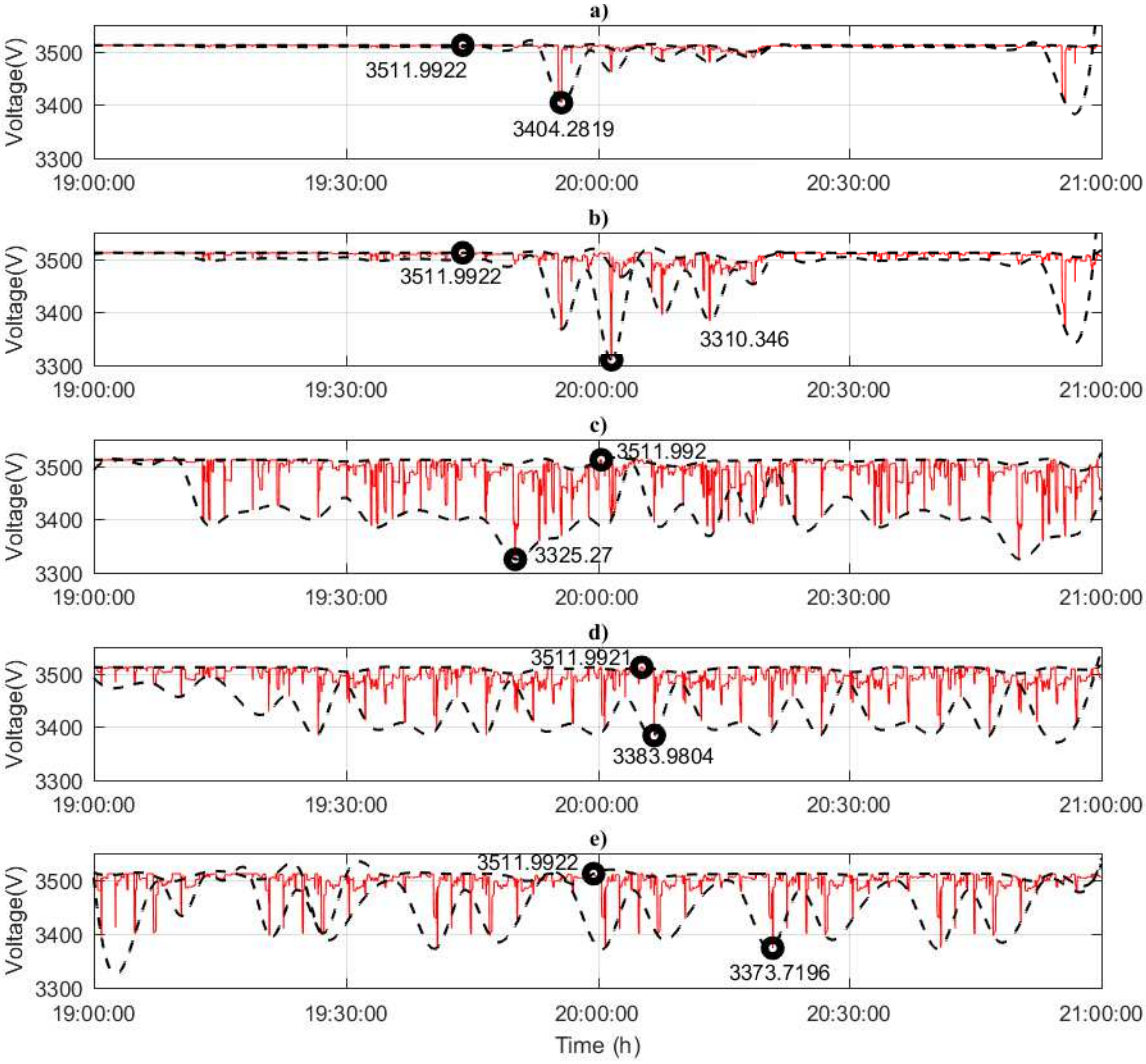


Figure 6-23: a) Voltage at EL Chorro substation along the simulation. b) Voltage at Pizarra substation along the simulation. c) Voltage at Los Prados substation along the simulation. d) Voltage at La Comba substation along the simulation. e) Voltage at Carvajal substation along the simulation.

Energy study

Taking into account previous studies in this chapter, the energies that each substation provides to the system will be analysed by using Fig. 6-24, where the energy evolution along the simulation is depicted. As it can be seen, the energy provided by each substation has dropped, because of the recovered energy by the ESS, which avoid supplying the trains when these systems have energy. Something interesting is "La Comba" substation behaviour, because as there is not regenerative energy going to catenary, it cannot deliver this energy into ac system again, becoming these system in a great alternative for reversible substations.

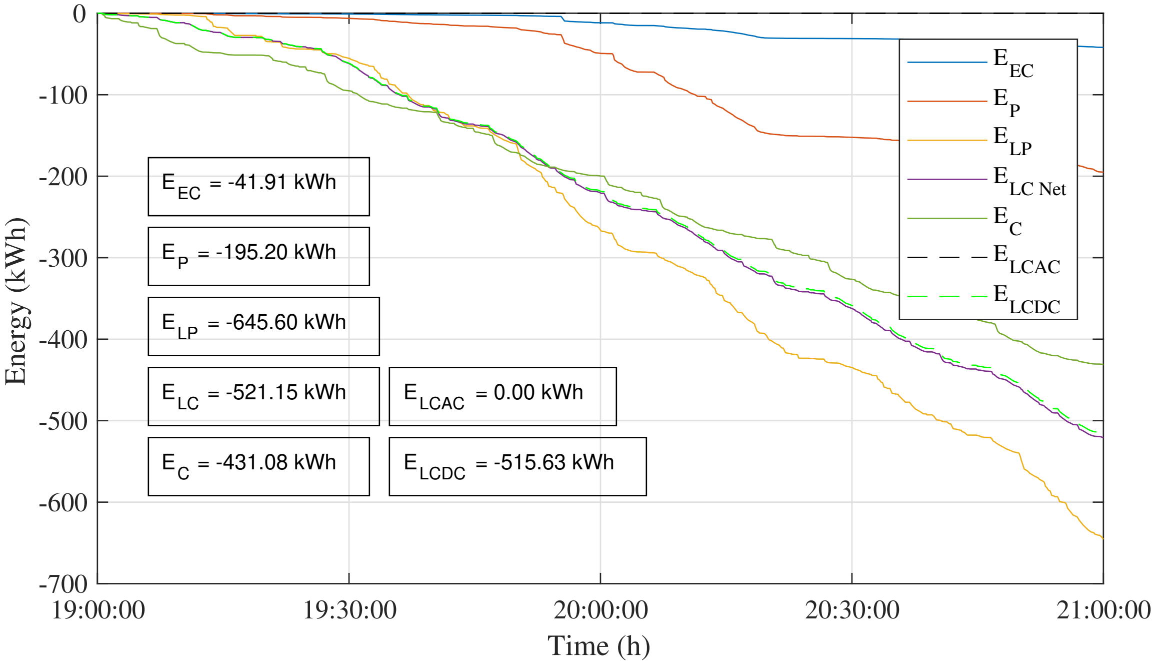


Figure 6-24: Energy evolution of each substation, with their final energy value.

It is not less important the analysis of the energy losses in catenary, which are depicted in Fig. 6-25. If a comparison between this scenario to the base case is done, it can be seen the energy losses have been decreased up to 27.69 kWh, because of the same reason that has been previously discussed. As the trains are supplied in certain moments by the OESS, there is not current in the catenary in those moments, so no losses exist.

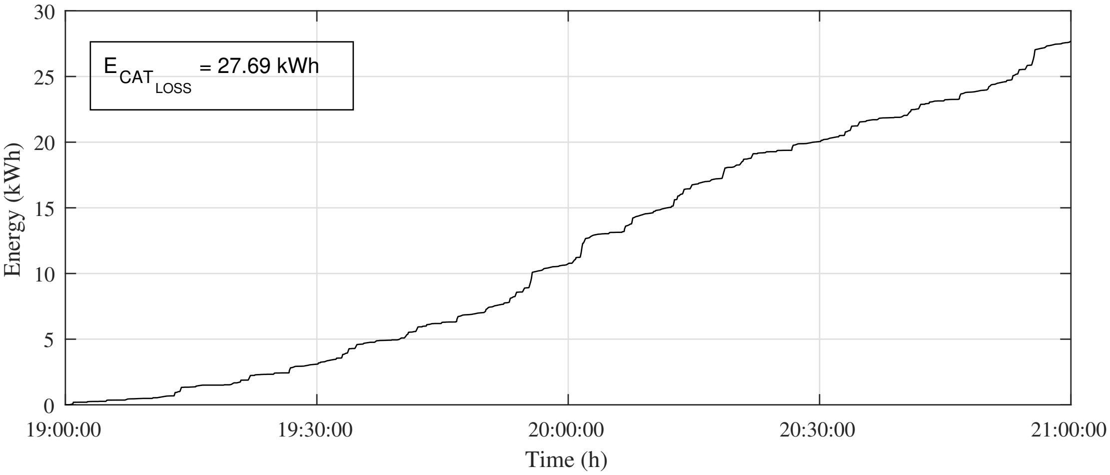


Figure 6-25: Power losses evolution in catenary.

6.3.2 Scenario: Off-board accumulation systems

In this scenario, Off-board Energy Storage Systems (Off-ESS) will be included in ”Los Prados” substation in order to recover and deliver the needed energy by the system, and also controlling the dc voltage. The intention of this scenario, as it was in the case of the OESS, is explain how Off-ESS work and how they affect to the system. These system can be used for avoiding reversible substations or for voltage control; nevertheless in the case of this project only the voltage control feature will be studied. Table 6.4 shows the characteristics of the Off-ESS.

Table 6.4: Off-ESS characteristics

Capacity	P_{maxD}	P_{maxC}	V_{ref}	dV1	dV2	dV3
120 kWh	2000 kW	200 kW	1.064	0.1	0.01	0.1

Notice that the Off-ESS selection must be done carefully, because it can destabilize the railway grid, due to it is a distributed generation element which is controlled in voltage. So depending on the voltage, the device will inject/absorb a great amount of energy on which can make the grid going towards the nose of the stability curve (P-V curve), having to disconnect the power system [39].

How Off-ESS work?

As [38] explains, Off-ESS are similar to OESS, in terms of technology (usually based in batteries or ultra-caps). however they have a higher capacity in order to provide or absorb a great amount of power from the system (acceleration or braking). They have a similar curve to OESS, where the SOC of the battery can limit the power.

However, this is not the only characteristic of Off-ESS, due to they also can regulate the voltage of the node they are connected by means injecting or absorbing power by following the curve depicted in 6-26.

With this device, the voltage is wanted to have as close as possible to V$_{ref}$, being possible to be varied ± dV2 with no changes in the system.

Once the voltage exceeds 1.074 (V$_{ref}$+dV2) the accumulator will start to be charged in order to reduce the voltage level of the point where it is connected. On the other hand, when the voltage is lower than 1.054 (V$_{ref}$-dV2), the battery is discharged against the grid, thus increasing the voltage of the grid. If the voltage level reaches V$_{ref}$ ± (dV2+dV1/dV3), the battery will be charged/discharged to its maximum power (P$_{max}$).

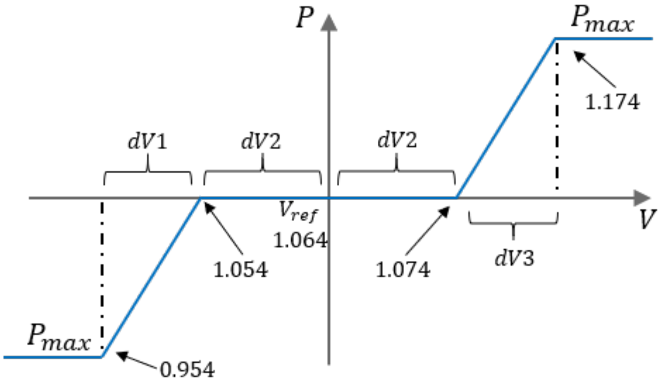


Figure 6-26: Off-board energy storage system scheme.

This behaviour will be explained through Fig. 6-27, where the evolution of catenary power and Off-ESS power are depicted in a), and in b) the voltage in per unit and also the State of Charge of the battery. These variables correspond to 10 minutes of the simulation.

Through the figure, the behaviour of the ESS can be analysed, taking into account the catenary voltage and the state of charge. As it can be seen, when the voltage exceeds 1.074, the battery start to absorb power, in order to alleviate the energy in the grid, and when the voltage decreases under 1.054, the other way around. Fig. 6-28 shows with a little more detail two of these instants.

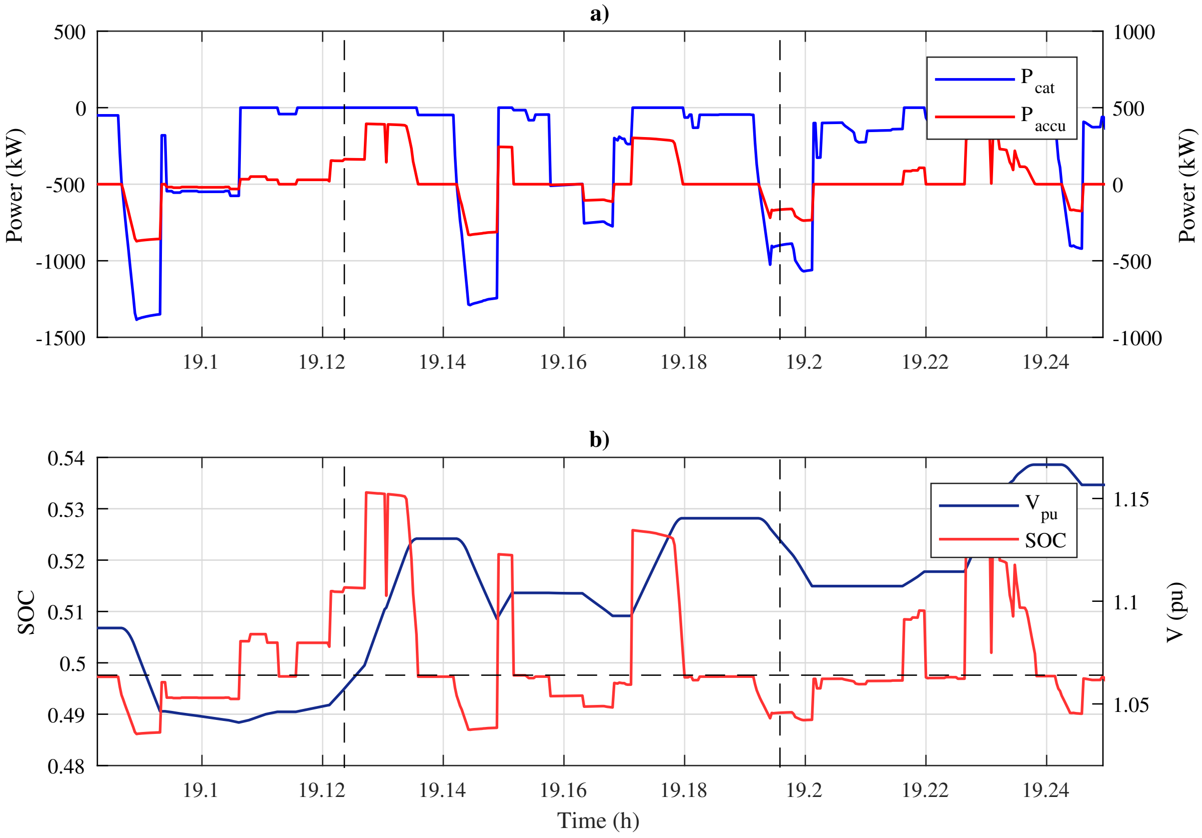


Figure 6-27: a) Catenary power and Power provided by Off-ESS. b) Accumulator voltage and its SOC.

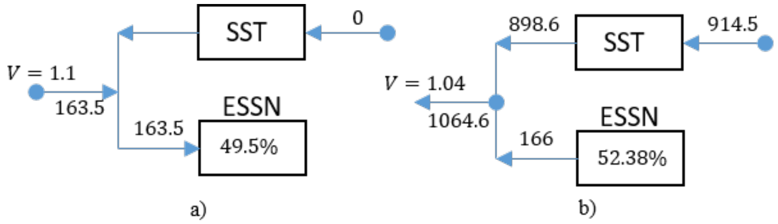


Figure 6-28: Off-board energy storage system example for explanation: a) Charging. b) Discharging.

Fig. 6-29 shows the voltage evolution of each substation. As it can be seen all voltage are more uniform, although the maximum and minimum values have increased. The Off-ESS has achieved that in average ” Los Prados” is quite close to 1.064 pu (3512 V).

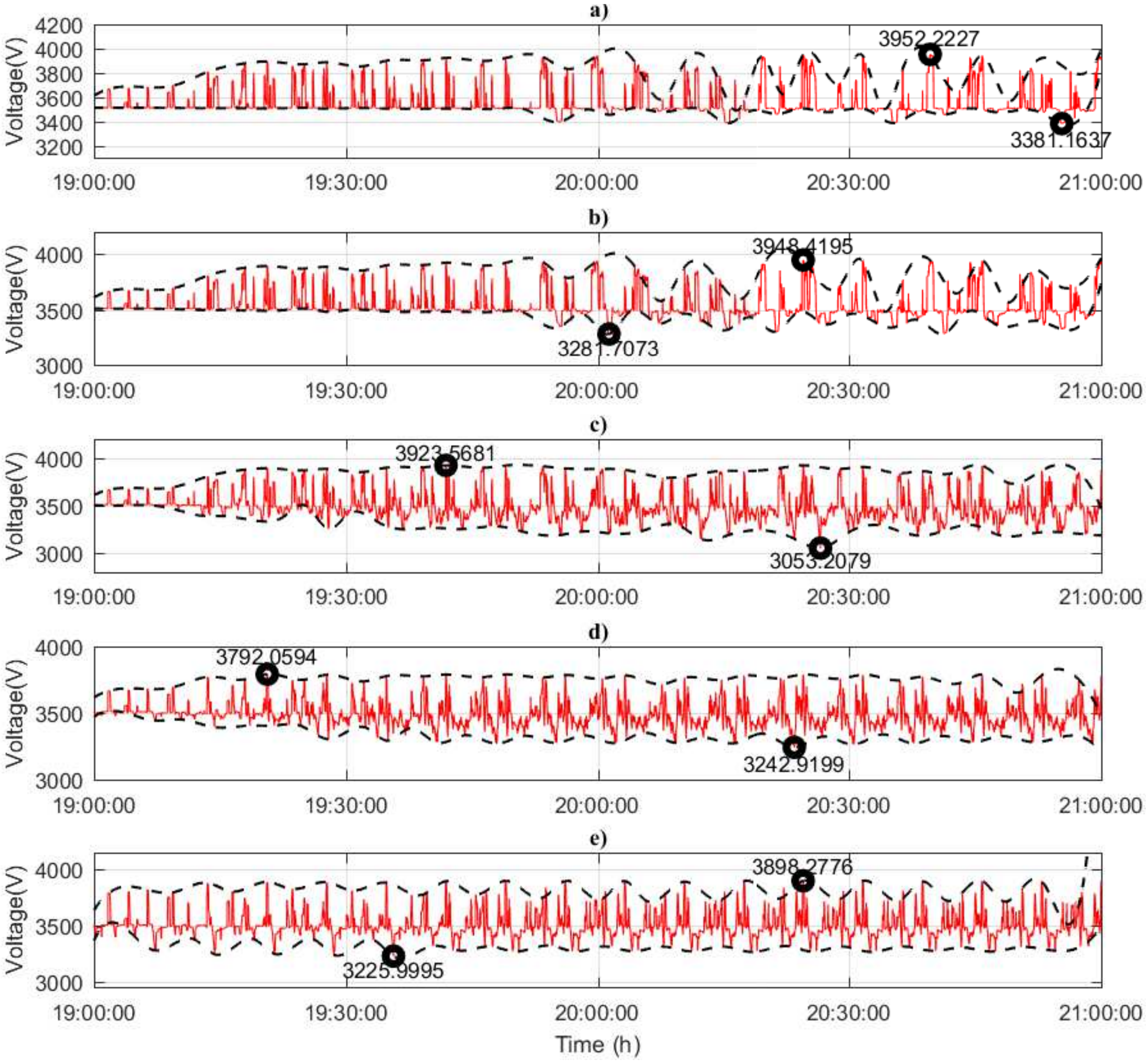


Figure 6-29: a) Voltage at EL Chorro substation along the simulation. b) Voltage at Pizarra substation along the simulation. c) Voltage at Los Prados substation along the simulation. d) Voltage at La Comba substation along the simulation. e) Voltage at Carvajal substation along the simulation.

Energy study

Once more an energy study of the grid will be carried out in order to know how the introduction of an Off-ESS affect the system.

Fig. 6-30 shows the provided energy evolution of each substation along the simulation. As it can be seen the total energy of each substation decreases due to the presence of the accumulator, on which injects energy into grid when the voltage decreases. In case of "La Comba" substation injects less energy into ac system, because of when the voltage increases and the Off-ESS absorbs energy from the system. This has been often the norm, because of the high voltage profile of the system.

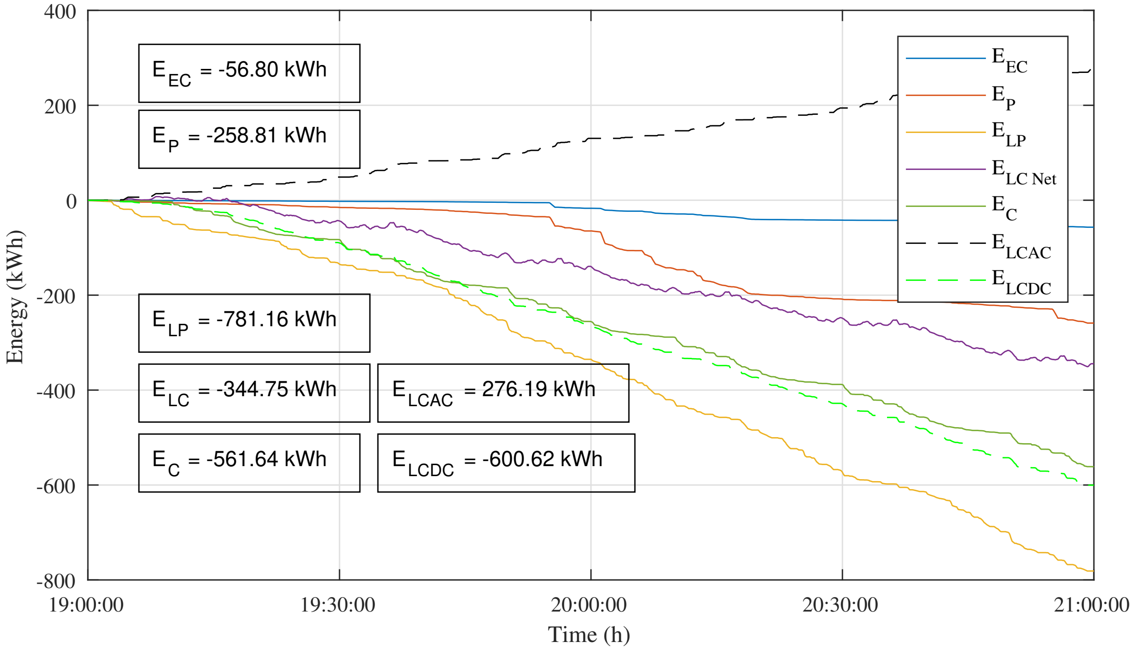


Figure 6-30: Energy evolution of each substation, with their final energy value.

In case of catenary losses, the introduction of this device has not affect so much, because of they are almost the same, increasing a little up to reach 95.62 kWh. Their evolution can be seen in Fig. 6-31.

Finally, the braking energy losses are analysed. Their evolution can be observed in Fig. 6-32, where as it can be seen, with the introduction of the Off-ESS, the total amount of braking energy losses decreases. This is caused by the voltage regulation of the storage system, which causes the average voltage level to decrease, which is a good for reducing these losses, as they increase with voltage.

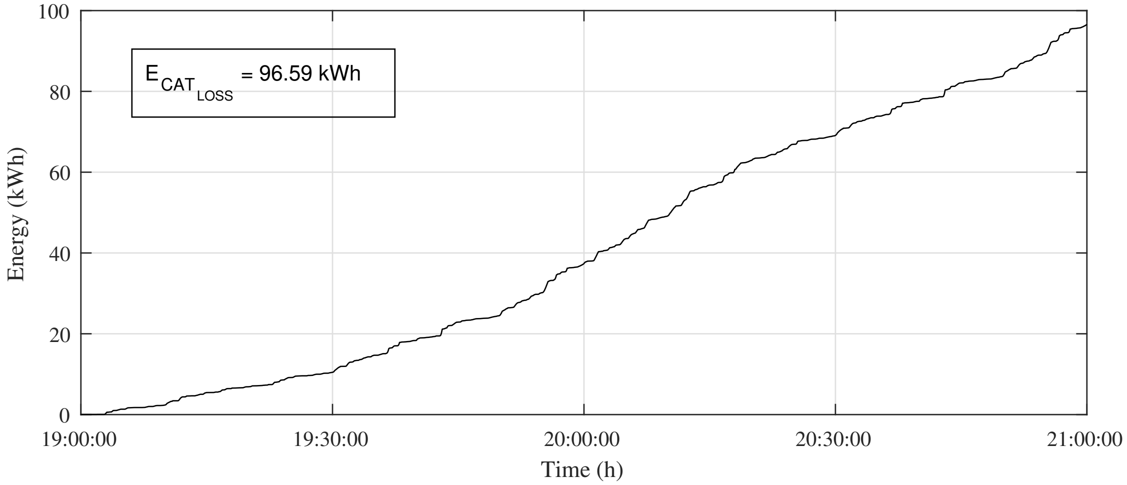


Figure 6-31: Power losses evolution in catenary.

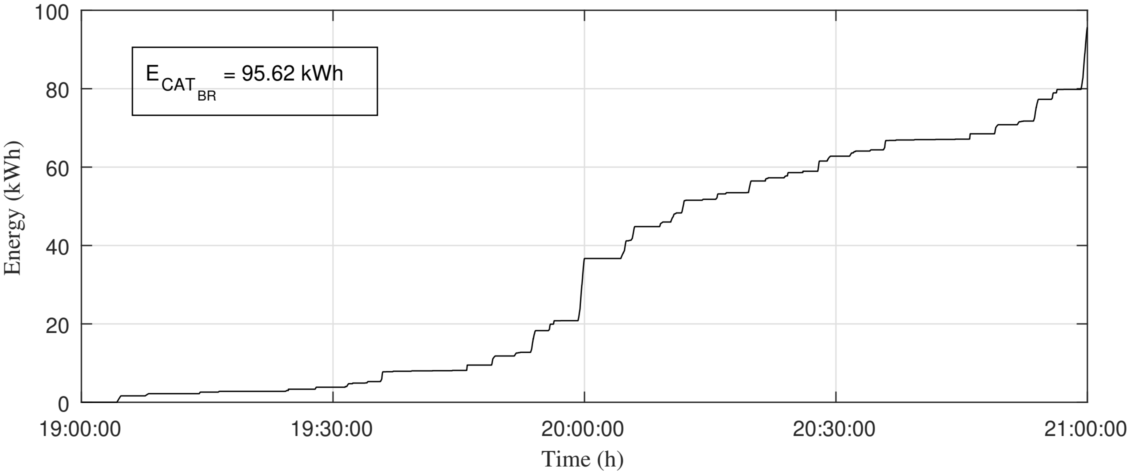


Figure 6-32: Total energy loss evolution in rheostats in two hours of simulation.

6.3.3 Scenario: Double train frequency

In this scenario the train frequencies of the base case will be doubled in order to see how voltages and energies along the system behaves (similar to previous cases). Therefore, in this case the trains from Málaga-Fuengirola route will leave each 10 minutes (with a total of 24 trains along the simulation), and trains from Málaga-Alora route each 30 minutes (6 trains along the simulation) in a total simulation of two hours.

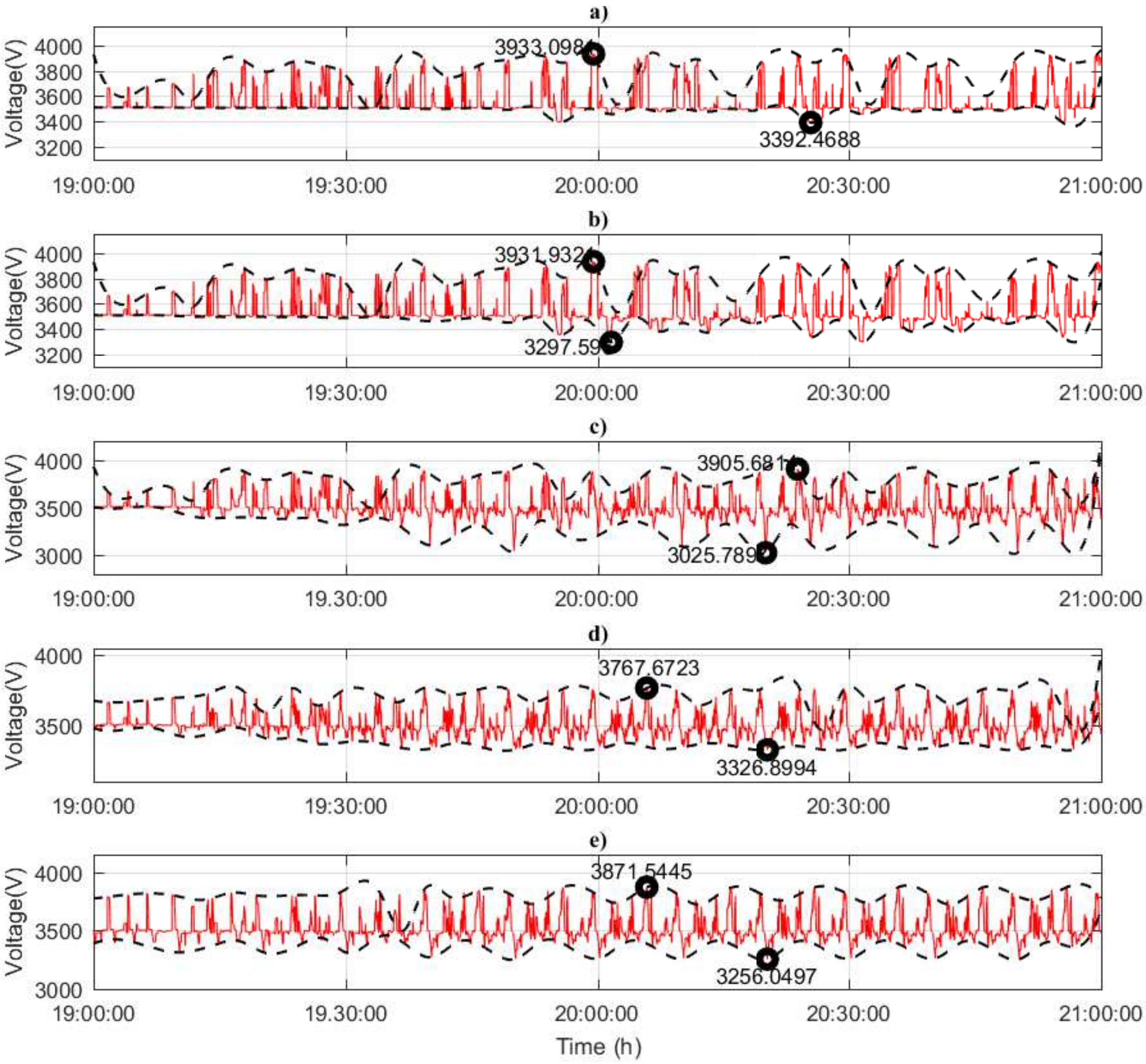


Figure 6-33: a) Voltage at EL Chorro substation along the simulation. b) Voltage at Pizarra substation along the simulation. c) Voltage at Los Prados substation along the simulation. d) Voltage at La Comba substation along the simulation. e) Voltage at Carvajal substation along the simulation.

Voltage profile

As previously studied, the voltage profile of each substation will be analysed, in order to understand what changes in behaviour have arisen by introducing this variation of the frequency of trains in the system.

This can be seen in Fig. 6-16, where the voltage evolution in all substations can be observed. The voltage magnitude has been increase, comparing this scenario to the base case, because of both the maximum voltage and minimum voltage are greater and lower, respectively, as it can be seen in the voltage envelope.

Once more, "Los Prados" substation has the highest voltage variation of all substations, because of it belongs to both routes.

Energy study

Once more the energy study is done, by studying the provided energy by each substation, as Fig. 6-34 depicts. As it was expected the energy of each substation is increase due to the increase of train frequency. Being the one that more increases "Los Prados" substation. One interesting thing is the reduction of the energy returned to the AC grid. This is due to a better use of the energy regenerated by the trains, which instead of returning it to the network, is consumed by other trains instead.

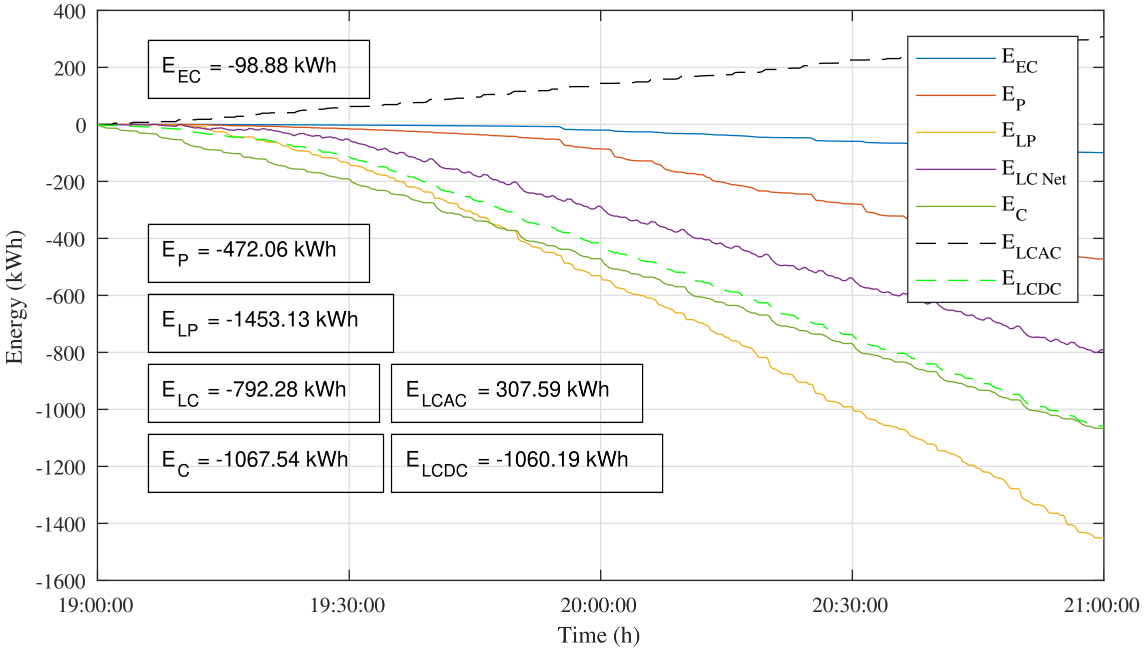


Figure 6-34: Energy evolution of each substation, with their final energy value.

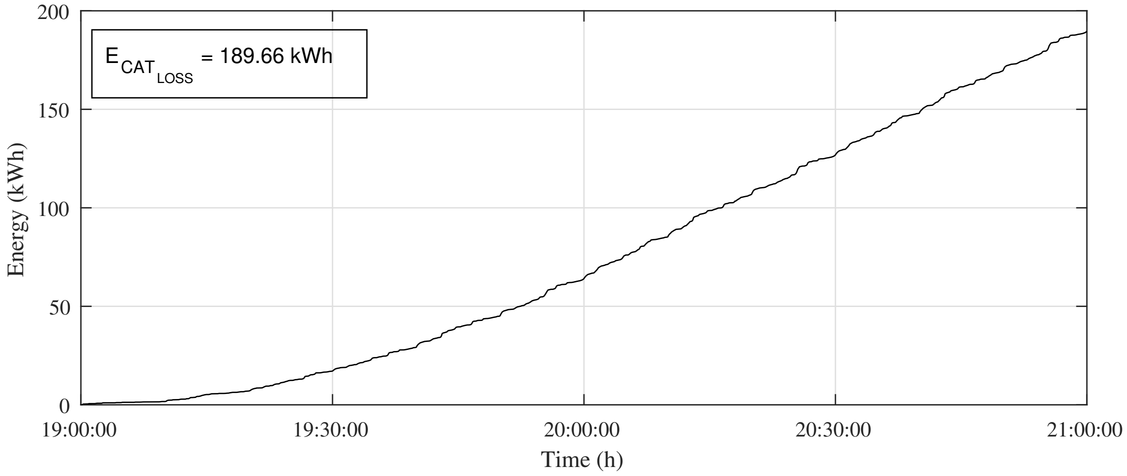


Figure 6-35: Energy losses evolution in catenary.

In case of catenary losses, as it can be seen they have increased up to reach 189.66 kWh, which is normal, because of there is more energy flowing the lines. This energy is almost double the energy of the base case.

Braking losses increase, but not linearly. The flow of trains is doubled, but it is not the case of braking losses (around 40 %).

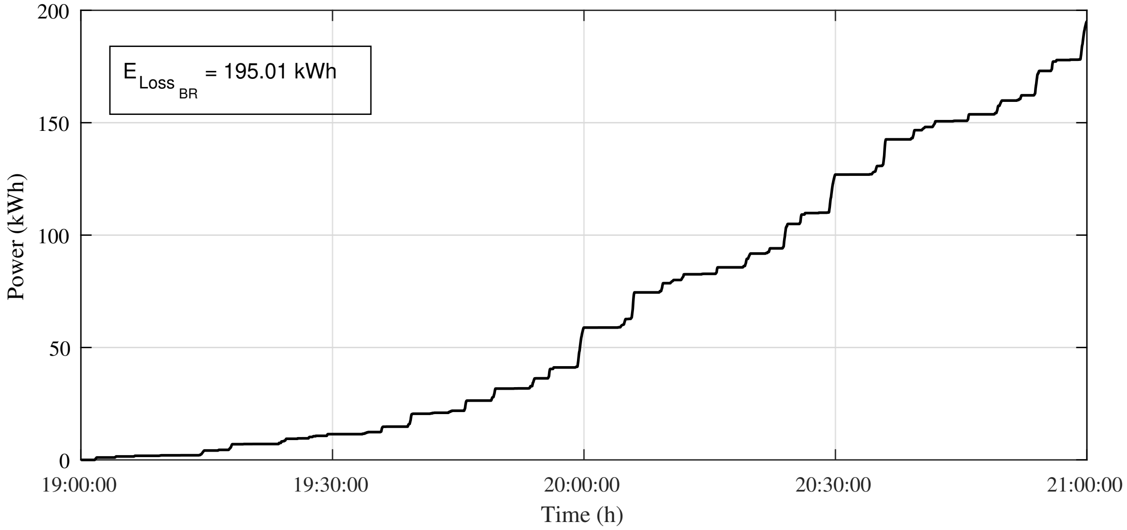


Figure 6-36: Total energy loss evolution in rheostats in two hours of simulation.

6.3.4 Scenario: Triple train frequency

In this final scenario, the train frequency of the base case will be tripled, in order to do a small study of how the energy losses in the system behave. Therefore, the trains from Málaga-Fuengirola route will leave each 7 minutes and 6 seconds (with a total of 36 trains along the simulation), and trains from Málaga-Alora route each 10 minutes (12 trains along the simulation) in a total simulation time of two hours.

Energy study

Fig. 6-37 shows the energy evolution provided by each substation. As in the previous case, the energy provided by each substation increases, except for the energy absorbed by "La Comba", which decreases. This is caused by the same reason as in the previous case, however, having more trains, the energy is better used within the system. The difference among this case and both studied cases previously (without taking into consideration the OESS scenario) are 25.58 and 68.71 kWh.

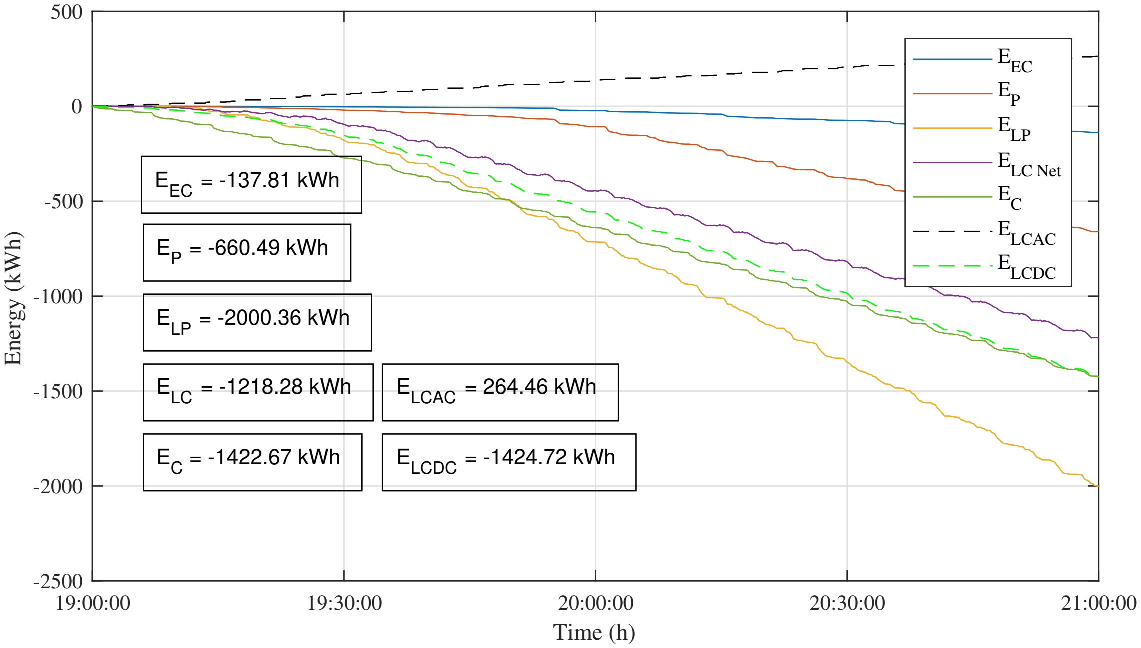


Figure 6-37: Energy evolution of each substation, with their final energy value.

The energy losses in the overhead line increase because of there is more current along the system, so there is more losses. The energy losses evolution is depicted in Fig. 6-38 reaching a value of 257.94 kWh.

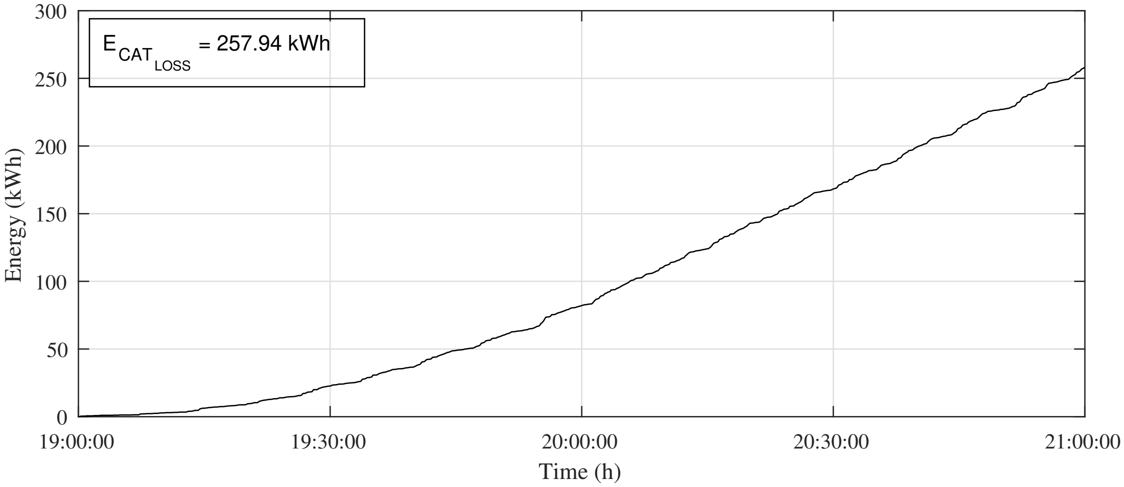


Figure 6-38: Energy losses evolution in catenary.

The braking losses increases again, because of the voltage profile also increases (is quite similar to the one depicted in Fig. 6-33). Its evolution is depicted in Fig. 6-39, increasing 93.58 %. In this case, it can be seen again that the evolution of these losses does not increase directly proportional to the frequency of the trains.

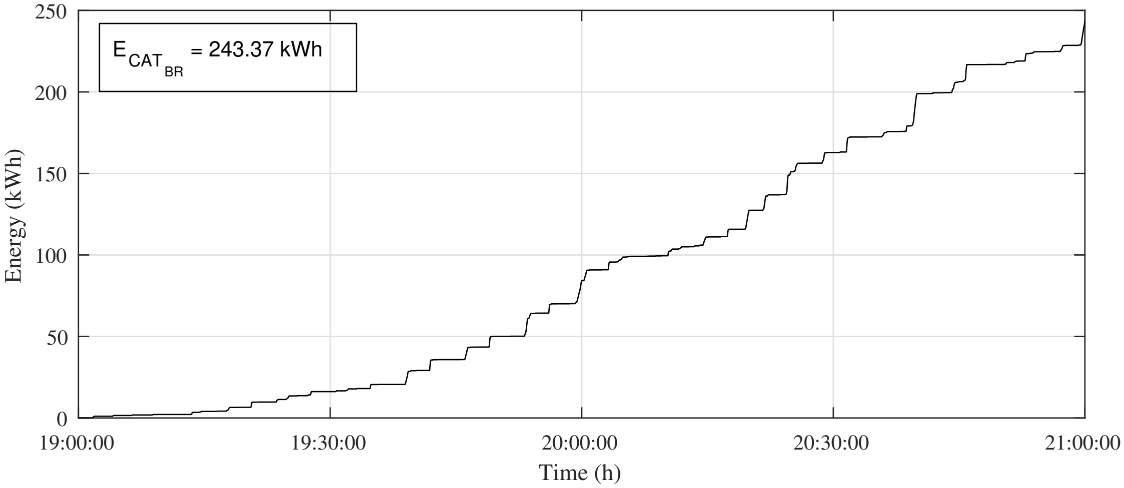


Figure 6-39: Total energy loss evolution in rheostats in two hours of simulation.

6.4 Conclusion

In this chapter several simulations of suburban railway network which connects three Spanish towns (Alora-Málaga-Fuengirola) have been done, in order to understand in a simple manner the operation of railway systems. Not only the simulation of the real system has been carried out, but also some modifications have been done in order to see how the system behaves. From the introduction of accumulation systems (on-board and off-board energy storage systems) up to the schedule modification of the trains to have more cars operating.

From these simulations, several conclusions can be extracted such as; the use of OESS can remove the necessity of bidirectional substations, as well as reducing the size of the infrastructure, due to the reduction of losses. This fact avoids giving back energy to the catenary, and also the burned energy in the braking resistors; the Off-ESS aid to control the catenary voltage, however its dimensioning is complicated because it can unstable the grid, due to they are controlled by voltage; finally, by modifying the schedule of the trains, the system is better exploited, being unnecessary to inject so much energy through the bidirectional substation. Furhermore the braking losses increases but they do not do it in a direct manner.

Chapter 7

Conclusions and Future Work

Conclusions

In this master thesis, a study about the different railway systems, since the different vehicle types (tramways, metro, suburban...), up to the description of the needed infrastructure for its operation have been carried out. This explanation has been done so that the nonexpert reader of the topic of this project understands the magnitude of these systems, and thus they are able to understand the important part of this document, which is the RailNeos 2.0 validation and the analysis of the railway network.

One of the main motivations of this project has been the DC simulator (RailNeos 2.0) validation, in which the original simulator (RailNeos 1.0) is compared to the new one, observing it does not only solve the problems of the first version (simulation speed, algorithm improvements achieving more consistent results...), but also introduces a more comfortable user interface, which allows inexperienced users approach the simulator without fear.

Hence, it can be concluded that, although it is still necessary to validate other railway networks during the internship that I am carrying out, the simulator works well, obtaining more accurate and real results than the original simulator.

Furthermore, a detailed analysis of a real railway network has been done, explaining in a simple manner how railway systems operate, which could be extrapolated for other networks without big problems.

Future work

As it was aforementioned, there is still room for work in this project, where it would be necessary to finish validating the tool with other railway systems, as well as several configuration of the program (links, accumulators, buses...), and also the simulations ESTEFI demands. However, this does not finish here, because it is possible that in a near future, the simulator includes also an ac simulator (for high-speed applications), and it will be needed verifying the results.

Finally, thanks to the experience gained with the simulator in this master thesis, different researches and publications can be done, such as an exhaustive study of how the different accumulation systems affect the network, or also seeing the effect that has the train frequency variation in a more detailed way.

Appendix A

Tutorial I: How to simulate a train in ITINER

In this appendix, a small tutorial for carrying out an ITINER simulation will be done, by explaining the different source files, the simulation procedure and how to extract the XTP file needed for the RailNeos 2.0 simulation. For doing the explanation, the information from the Darmstadt tramway provided by CAF TE will be used. This information is always provided by people from preliminary design, which is a department of the company.

In order to make the simulation, as it was explained in the main document, three excel files must be taken into consideration. These files are:

- Vehicle.
- Route.
- Simulation.

Therefore the configuration of each of them will be done in the following section taking into account the input information.

A.1 Vehicle

This excel file is composed by several sheets where the input information related to the vehicle is introduced. The complete list of the excel sheets is: Vehicle data, gearbox, motor-performances, motor-losses, inverter, filter, auxiliary converter, rotating masses, breakers, braking discs, ACR, motor-efficiency, inverter-losses, rectifier, transformer, power pack generator and consumption map-diesel engine. In this case only the first eight sheets will be used, which are the most common for the most frequent trains. As it can be seen, this simulator allows simulating very different parameters of the train, from the brake parameters up to simulate depending on the type of energy source (DC, AC or diesel).

A.1.1 Vehicle data

The vehicle data is one of the most important parameters, because of it will allow calculating the necessary energy for moving the train. This is introduced into the vehicle data sheet, with the information that Table A.1 shows.

Table A.1: General characteristics

Mass [Tn]	52.568
Rotating mass – motor/towing boggie [Tn]	(3*1.324+1*0.516)
Train length [m]	38.676
Maximum train speed [km/h]	70
Wheel radius [mm]	295
Track gauge (track width +2*rail width) [mm]	1505
Traction Jerk [m/s^3]	1
Catenary receptivity [%]	0
Traction/Braking catenary voltage [V]	700/700
Maximum DC Link current [A]	-

As it can be seen, most of the train parameters are introduced in Table A.1. However, they are not the only parameter that must be set. The drag parameters used for calculate the force the train must overcome for moving are needed. They can be obtained from Table A.2.

Once these parameters are known, the force can be calculated with (A.1), on which

Table A.2: Drag characteristics

a [kN/Tn]	0.03224
b [kN/(Tn*(km/h)]	0
c [kN/(Tn*(km/h)^2)]	0
A [kN]	0
B [kN/(km/h)]	0.0657495
C [kN/(km/h)^2]	$1{\cdot}10^{-6}$
Wind speed [km/h]	-

depends on the train speed, and their mass. Note that the value of C in this case is zero, but the program does not allow it, so it is mandatory to use a small value of C.

$$\begin{cases} R_{drag}\,[kN] = (a + b \cdot v + c \cdot v^2) \cdot M[T_n] + (A + B \cdot v + C \cdot v^2) \\ \text{with } v \text{ in } km/h \end{cases} \tag{A.1}$$

Besides the previous tables, a new table which describes the traction architecture must be fulfilled. This is Table A.3, which shows the traction architecture for traction and for braking, on which depending on the the configuration can describe very different railway systems.

Table A.3: Traction architecture definition

Traction	Engines/ PowerPack	Catenary (0: No/ 1: DC / 2:AC)	Transformers	Rectifiers	Inductances
	0	1	0	0	3
	Ancilliary	Brake resistors	Traction chest	Inverter/chest	Motor/inverter
	1	6	3	2	2
Brake	Engines/ PowerPack	Catenary (0: No/ 1: DC / 2:AC)	Transformers	Rectifiers	Inductances
	0	1	0	0	3
	Ancilliary	Brake resistors	Traction chest	Inverter/chest	Motor/inverter
	1	6	3	2	2

Once the traction architecture table is fulfilled, the traction architecture scheme is created, looking like the scheme than Fig. A-1 shows.

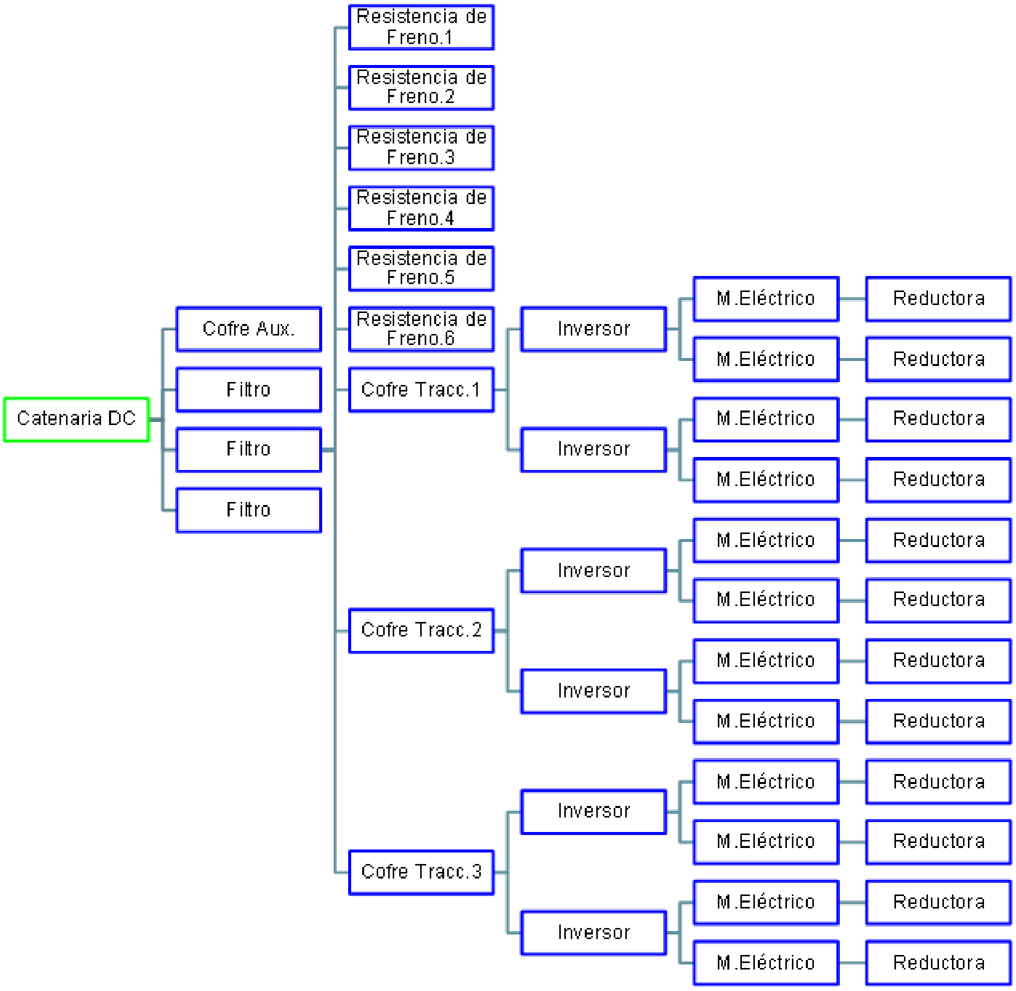


Figure A-1: Traction architecture.

A.1.2 GearBox

The gearbox that reduces the speed of rotation of the engine on the wheels thanks to its transmission ratio is configured in this sheet. Here, the transmission ratio and the efficiency for a speed range is set, as Table A.4 shows.

A.1.3 Motor - performance

In this sheet, one of the most important parameters of a electric train is characterized, on which is the electrical machine. The characterization is done by its mechanical

Table A.4: Gearbox configuration

Gearbox	
Transmission ratio	5.44
Type	Urbos 3
Rotational speed [rpm]	Efficiency [pu]
0	0.975
5000	0.975

characteristic curve, as the one that Fig. A-2 shows. In this case, the total curve is not introduced in the program, if not only the important points. These are the maximum force at 0 speed (first point) up to reach the speed where the force starts to vary with speed (second point). The third point is the last point of the curve (higher speed and lower force). Note that if the mechanical curve present a region where the force varies by a $1/v^2$ ratio, another region exists and other point must be included. Table A.5 shows the information that must be included.

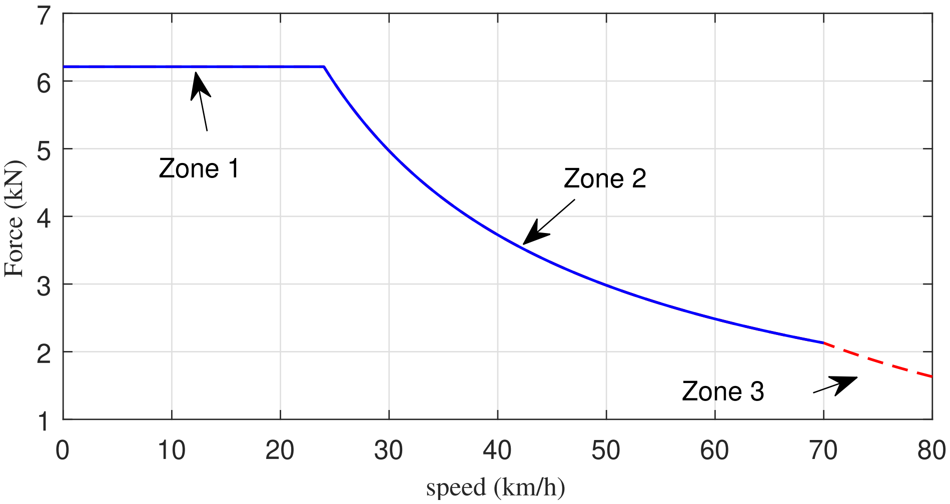


Figure A-2: Mechanical characteristic.

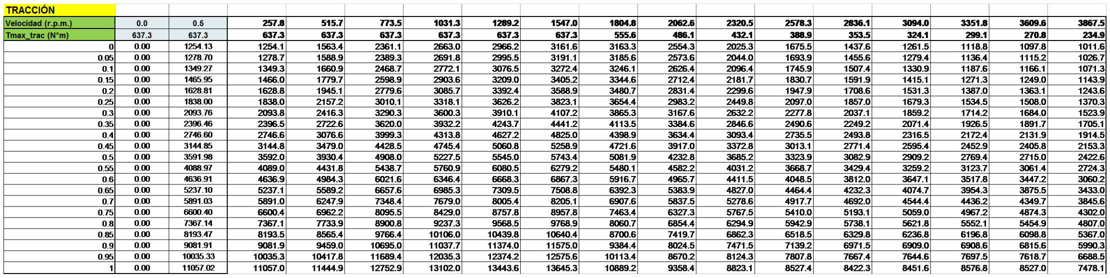
Note the traction force and the electric force are introduced by each motor and the total brake will be the total brake force for braking the train. In this case, because of the weight of the train, the selected motor will be EL0.

Table A.5: Motor-performance characteristics

Traction			Total brake			Electric brake		
F (kN)	v (km/h)	Type	F (kN)	v (km/h)	Type	F (kN)	v (km/h)	Type
6.2113	0	1	-72.873	0	1	-6.0723	2	1
6.2113	24	2	-72.873	70	1	-6.0723	70	1
2.1296	70	2						

A.1.4 Motor-Losses

The losses of the machine can be introduced into the program in two ways. By a constant relationship or by using a more accurate manner, such as the efficiency matrix that is introduced in this excel sheet. Note that they are introduced for traction and for braking. Fig. A-3 shows a screen-shot from the one used in Darmstadt tramway.



TRACCIÓN																
Velocidad (r.p.m.)	0.0	0.5	257.8	515.7	773.5	1031.3	1289.2	1547.0	1804.8	2062.6	2320.5	2578.3	2836.1	3094.0	3351.8	3609.6	3867.5
Tmax_trac (N*m)	637.3	637.3	637.3	637.3	637.3	637.3	637.3	637.3	555.6	486.1	432.1	388.9	353.5	324.1	299.1	270.8	234.9
0	0.00	1254.13	1254.1	1563.4	2361.1	2663.0	2966.2	3161.6	3163.3	2554.3	2025.3	1675.5	1437.6	1261.5	1118.8	1097.8	1011.6
0.05	0.00	1278.70	1278.7	1588.9	2389.3	2691.8	2995.5	3191.1	3185.6	2573.6	2044.0	1693.9	1455.6	1279.4	1136.4	1115.2	1026.7
0.1	0.00	1349.27	1349.3	1660.9	2468.7	2772.1	3076.5	3272.4	3246.1	2626.4	2096.4	1745.9	1507.4	1330.9	1187.6	1166.1	1071.3
0.15	0.00	1465.95	1466.0	1779.7	2598.9	2903.6	3209.0	3405.2	3344.6	2712.4	2181.7	1830.7	1591.9	1415.1	1271.3	1249.0	1143.9
0.2	0.00	1628.81	1628.8	1945.1	2779.6	3085.7	3392.4	3588.9	3480.7	2831.4	2299.6	1947.9	1708.6	1531.3	1387.0	1363.1	1243.6
0.25	0.00	1838.00	1838.0	2157.2	3010.1	3318.1	3626.2	3823.1	3654.4	2983.2	2449.8	2097.0	1857.0	1679.3	1534.5	1508.0	1370.3
0.3	0.00	2093.76	2093.8	2416.3	3290.3	3600.3	3910.1	4107.2	3865.3	3167.6	2632.2	2277.8	2037.1	1859.2	1714.2	1684.0	1523.9
0.35	0.00	2396.46	2396.5	2722.6	3620.0	3932.2	4243.7	4441.2	4113.5	3384.6	2846.6	2490.6	2249.2	2071.4	1926.5	1891.7	1705.1
0.4	0.00	2746.60	2746.6	3076.6	3999.3	4313.8	4627.2	4825.0	4398.9	3634.4	3093.4	2735.5	2493.8	2316.5	2172.4	2131.9	1914.5
0.45	0.00	3144.85	3144.8	3479.0	4428.5	4745.4	5060.8	5258.9	4721.6	3917.0	3372.8	3013.1	2771.4	2595.4	2452.9	2405.8	2153.3
0.5	0.00	3591.98	3592.0	3930.4	4908.0	5227.5	5545.0	5743.4	5081.9	4232.8	3685.2	3323.9	3082.9	2909.2	2769.4	2715.0	2422.6
0.55	0.00	4088.97	4089.0	4431.8	5438.7	5760.9	6080.5	6279.2	5480.1	4582.2	4031.2	3668.7	3429.4	3259.2	3123.7	3061.4	2724.3
0.6	0.00	4636.91	4636.9	4984.3	6021.6	6346.4	6668.3	6867.3	5916.7	4965.7	4411.5	4048.5	3812.0	3647.1	3517.8	3447.2	3060.2
0.65	0.00	5237.10	5237.1	5589.2	6657.6	6985.3	7309.5	7508.8	6392.3	5383.9	4827.0	4464.4	4232.3	4074.7	3954.3	3875.5	3433.0
0.7	0.00	5891.03	5891.0	6247.9	7348.4	7679.0	8005.4	8205.1	6907.6	5837.5	5278.6	4917.7	4692.0	4544.4	4436.2	4349.7	3845.6
0.75	0.00	6600.40	6600.4	6962.2	8095.5	8429.0	8757.8	8957.8	7463.4	6327.3	5767.5	5410.0	5193.1	5059.0	4967.2	4874.3	4302.0
0.8	0.00	7367.14	7367.1	7733.9	8900.8	9237.3	9568.5	9768.9	8060.7	6854.4	6294.9	5942.9	5738.1	5621.8	5552.1	5454.9	4807.0
0.85	0.00	8193.47	8193.5	8565.4	9766.4	10106.0	10439.8	10640.4	8700.6	7419.7	6862.3	6518.5	6329.8	6236.8	6196.8	6098.8	5367.0
0.9	0.00	9081.91	9081.9	9459.0	10695.0	11037.7	11374.0	11575.0	9384.4	8024.5	7471.5	7139.2	6971.5	6909.0	6908.6	6815.6	5990.3
0.95	0.00	10035.33	10035.3	10417.8	11689.4	12035.3	12374.2	12575.6	10113.4	8670.2	8124.3	7807.8	7667.4	7644.6	7697.5	7618.7	6688.5
1	0.00	11057.02	11057.0	11444.9	12752.9	13102.0	13443.6	13645.3	10889.2	9358.4	8823.1	8527.4	8422.3	8451.6	8576.8	8527.0	7478.1

Figure A-3: Traction motor-losses matrix.

A.1.5 Inverter

The inverter efficiency can be characterized in the same way than the motor, with a constant efficiency or with a matrix. However in this case, as the inverter efficiency is quite high, using the constant efficiency is enough. Table A.6 shows the inverter efficiency for traction and braking.

A.1.6 Filter

The filter is used for remove the possible harmonics from the catenary. There are two ways to compute its efficiency. By using a constant efficiency, depending on its

Table A.6: Inverter efficiencies

Traction		Brake	
Motor speed (rpm)	η (pu)	Motor speed (rpm)	η (pu)
0	0.98	0	0.98
5000	0.98	5000	0.98

current or by using an equivalent filter resistance as equivalent circuit. In this case the equivalent resistance is used and it has a value of 51.5 mΩ.

A.1.7 Auxiliary converter

The auxiliary converter is used for transform the energy from the catenary to a more suitable voltage for being used to the ancillary services of the train. The values used are shown in Table A.7.

Table A.7: Auxiliary converter efficiencies

Auxiliary converter	
Power [kW]	Efficiency [pu]
0	0.98
50000	0.98

A.2 Route

This excel book is also composed by several sheets, where the input information regarding route in introduced. The complete list of excel sheets is: General information, vertical profile, stations, horizontal profile, speed limits, acceleration limits, performance, coasting, conduction way, ancillary, tunnel factors, catenary, hybridization and fuel cells. However in this case, the only sheets that will be used, being a simple case, will be the first three.

Special mention to horizontal profile where the characteristics of the curves and their location are set, as well as the possible superelevation needed for making in a proper manner the curves. Notice the vertical and horizontal profiles are usually given by preliminary projects directly by tables or also by planes, where the information must be carefully extracted.

Notice that normally, there are to fill at least two different route excel files, because of the route is not plane, and it is quite common that trains go through a path in one direction and come back from another in the other direction.

A.2.1 General information

In this excel sheet, the only thing that must be done is to set the use of some sheet of the excel file in order to take them into account in the final simulation, as well as the maximum speed that on this occasion is 70 km/h and the acceptance of energy from the catenary that will be 0%. In this case, only the vertical profile will be set.

A.2.2 Vertical profile

The vertical profile shows how different heights of the route vary, which is quite important for the train consumption. The information is usually introduced by kilometre and its slope, as Table A.8 shows.

Fig. A-4 shows the actual vertical profiles created with the information from Table A.8. Note that for the come back simulation, the vertical profile will change.

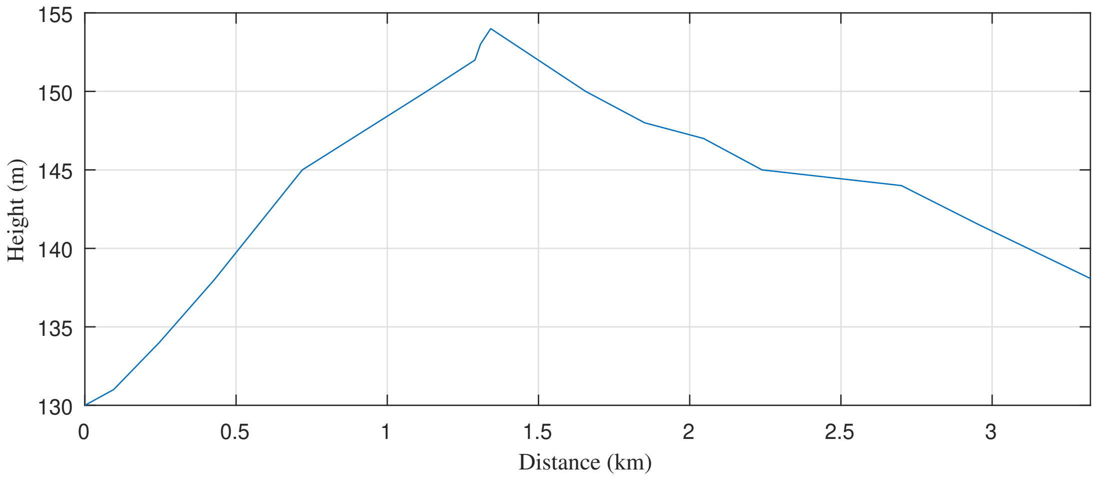


Figure A-4: Vertical profile.

Table A.8: Vertical profile table

Pk [km]	Slope [‰]	Height [m]
0.000	10.53	130.00
0.095	19.87	131.00
0.246	21.98	134.00
0.428	24.05	138.00
0.719	12.17	145.00
1.130	12.50	150.00
1.290	55.56	152.00
1.308	29.41	153.00
1.342	-12.74	154.00
1.656	-10.26	150.00
1.851	-5.13	148.00
2.046	-10.36	147.00
2.239	-2.17	145.00
2.700	-9.73	144.00
2.957	-9.29	141.50
3.226	0.00	139.00

Table A.9: Stations

PK	t_{stop}	v_{max}	Name	Schedule	Stop type	Pass. Out /	I_{max}	Arrival/ Depat
0.000	0.00	0.00	Mittelschneise	-	0.00	-	-	-
1.308	20.00	0.00	Malchen	-	0.00	-	-	-
3.226	0.00	0.00	Im Güldenen Wingert	-	0.00	-	-	-

A.2.3 Stations

In this excel sheet, the different stations, with the duration of the stops and their names are set. Table A.9 shows the different stations of this instance.

A.3 Simulation

Simulation excel file is used for configuring which are going to be the outputs of the simulation. It is composed of two excel sheet, which are the exportation sheet and simulations sheet. Notice it is important to start the name of this simulation file as “Simu_”, in order to do not get errors.

A.3.1 Exportation

ITINER simulations are used for obtaining the XTP files used in RailNeos 2.0, so the simulation must be focused in the power consumption, obtaining the complete power consumption. However this application is thought for other applications, so the energy consumption, the speed profile and other parameters can be extracted easily.

Table A.10: Simulation table

Simulation	Exporting results	Vehicle
EMU_DARMSTADT_ELO_IDA	Consumption_EMU_DARMSTADT_ELO_IDA	Vehicle.xlsm

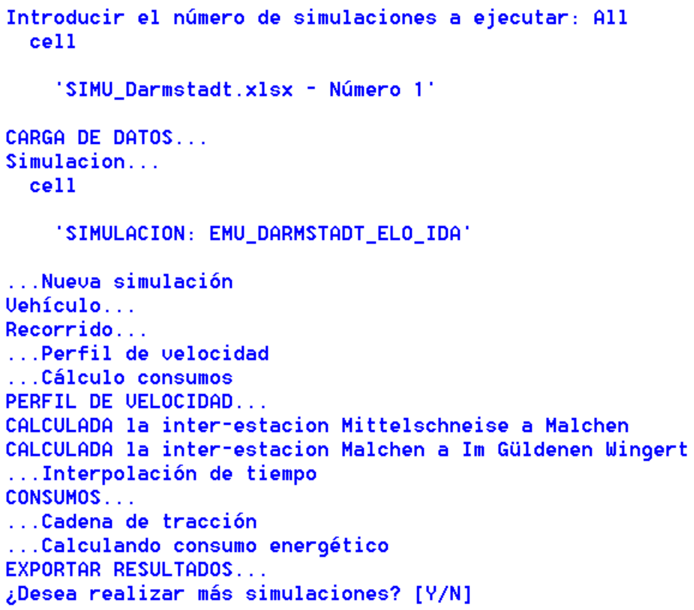
Route				Consumption	
Name	PK$_0$	PK$_f$	Δkm	Calculation	Aux. [kW]
Route.xls	0	3.226	0.01	Yes	11.2

A.3.2 Simulations

This sheet is used for configuring and saying to the solver, which vehicle and route excel files must use. Note that the name of both excel files must be written with their extension. It is also important setting which are the initial kilometre point and the final. Take into account they must match with the ones of route file. Table B.1 shows the needed information for the simulation, although there are other parameters that are used for other applications

A.4 Simulation interface

In order to simulate the system, a Matlab compiler must be installed and the executable of ITINER must be within the same folder than simulation, vehicle and route files. It is used through the cmd terminal of Windows as the screen-shot that Fig A-5. shows. Note this simulation must be done for at least one round trip, unless the vertical profile is flat.



```
Introducir el número de simulaciones a ejecutar: All
  cell

    'SIMU_Darmstadt.xlsx - Número 1'

CARGA DE DATOS...
Simulacion...
  cell

    'SIMULACION: EMU_DARMSTADT_ELO_IDA'

...Nueva simulación
Vehículo...
Recorrido...
...Perfil de velocidad
...Cálculo consumos
PERFIL DE VELOCIDAD...
CALCULADA la inter-estacion Mittelschneise a Malchen
CALCULADA la inter-estacion Malchen a Im Güldenen Wingert
...Interpolación de tiempo
CONSUMOS...
...Cadena de tracción
...Calculando consumo energético
EXPORTAR RESULTADOS...
¿Desea realizar más simulaciones? [Y/N]
```

Figure A-5: Simulation interface through CMD terminal.

A.5 Output file

Once the simulations is carried out, an excel file that is called “Consumption_EMU_DARMSTADT_ELO_IDA” is created. Within this file there is a sheet that is called Powers on which we are interested in. The needed columns are PK (km) that must be transformed to m, also the time column and finally the catenary power- traction column. These three columns must be copied into other excel file and then exporting them as csv (separated by semicolons). After that the file must be opened with a memo pad program and saving it as .text file.

Appendix B

Tutorial II: How to create a RailNeos 2.0 simulation

In this appendix, a small tutorial for carrying out a RailNeos 2.0 simulation will be done, taking into account the following information. Note this information is provided as in the case of ITINER, by people from preliminary project, unless the real position and number of substation are not predefined, and they must be studied by means of the tool (It is not the case of this tutorial).

- Rated values of each substation.
- Real position of each substation and station.
- Length of each line.
- XTP files.
- Schedules.

In this tutorial, an explanation for simulating a suburban system which connects three Spanish towns, such as “Málaga-Fuengirola” and “Málaga-Alora” are going to be done. The data of this system is the same, that in Chapter 5 was used for validating the tool, and also in chapter 6 for analysing the railway system. Fig. B-1 shows the scheme of the grid Notice that the Bobadilla substation will be not taken into account for being so far away.

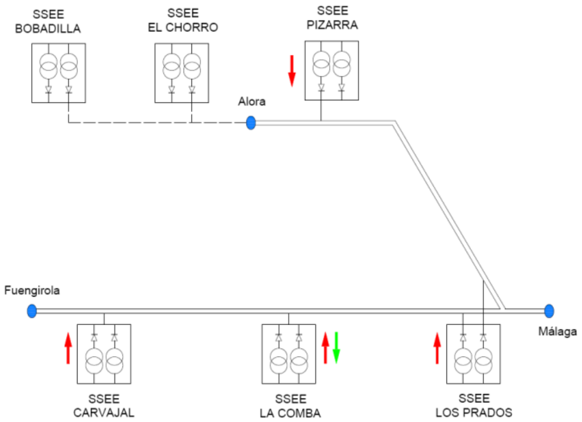


Figure B-1: Initial scenario of a suburban system [validation].

B.1 Configuration

In the network configuration, only the base power (in MVA) of the system is selected. This base power will be common to all elements and voltage levels of the simulation. This is because how the program works (in per unit). The system uses per default 1 MVA, and it will be the selected value for this simulation. But it can be changed if any convergence problem appears.

B.2 Base voltages

In this section, the different base voltages can be configured. Each node will be associated to one of these bases. However in this case, as the system works at 3000 V, only one base voltage is selected.

B.3 Nodes

In this section the position of each node is parametrized, as well as their electrical configuration. In order to introduce the physical location of each node, and thus obtaining a scheme similar to reality, the Google Earth program is used, and therefore, each station and substation will have their actual position. Fig. B-2 shows both "Málaga-Fuengirola" and "Málaga-Alora" routes.

Figure B-2: Actual position in Google Earth.

The actual position of all points from Fig. B-1 and Fig. B-2 are disaggregated in Table B.1, where the degrees will be the units, and the minutes and seconds the decimals, and the west position is taken as abscissa and north as ordinate.

Table B.1: Actual position of the railway system

El Chorro – Substation (EL)	X(4.4534), Y(36.5433)
Alora – Station	X(4.4158), Y(36.4912)
Pizarra – Substation (P)	X(4.4242), Y(36.4552)
Los Prados – Substation (LP)	X(4.2834), Y(36.4147)
Málaga – Station	X(4.2554), Y(36.4245)
La Comba – Substation (LC)	X(4.3140), Y(36.3612)
Carvajal – Substation (C)	X(4.3531), Y(36.3418)
Fuengirola - Station	X(4.3725), Y(36.3230)

Once this is known, the configuration of each node must be done, taking into account that the configuration of the stations will be always the same, because of they are disconnected from AC (type 0), so the unique important parameter is the base voltage, which must match with the one from the route they belong to.

In case of the substations, all of them as Fig. 1 shows are unidirectional (type 3), minus "La Comba" substation, which is bidirectional (type 2) although with deadband (in this case 40 V). All the information from all substations will be shown in the following Table B.2. Note that all substations will be earthed.

The parameters of the reverse and forward resistance (from the node characteristic) are calculated by the parameter calculator [38]. However, there may be cases where these values are not known, and they must be placed by try and fail, or for

Table B.2: Parameters of the substations

Name	R_{earth} [Ω]	V_{base} [V]	V_0 [V]	Type	S [MVA]	U_{cc} [%]
El chorro	5	3300	3512	3	3.3	10.66
Pizarra	5	3300	3512	3	6.6	10.615
Los Prados	5	3300	3512	3	6.6	9.8
La Comba	5	3300	3512	2	6.6	9.915/9.87
Carvajal	5	3300	3512	3	6.6	9.535

instance, in case of having a system with all unidirectional substations, that one of them must be set as bidirectional, but with the reverse resistance much higher than the forward, and this value must be set manually.

B.4 Trains

In this simulation only one type of train will be used, being enough the configuration of only one. In the configuration of the train, the traction and braking efficiency must be configured (in this case both at 100%), and also the traction and braking curves. See [38] in order to know what the meaning of those parameters is.

B.5 Lines

In order to introduce the train route, first of all, the lines which interconnect the different nodes must be set. In this configuration, the parameters of the different lines that Table B.3 must be included into the program. See [38] for more information about the other configurations.

Table B.3: Characteristics of the lines

Name	$\text{Length}_{pos}/\text{Length}_{neg}$ [km]	R_{pos}/ R_{neg} [mΩ/km]	Type
EL Chorro-Alora	12.494	50/14	Conventional
Alora-Pizarra	7.338	50/14	Conventional
Pizarra-Los Prados	25.084	50/14	Conventional
Fuengirola-Carvajal	4.374	50/14	Conventional
Carvajal-La comba	7.848	50/14	Conventional
La comba-los prados	14.3	50/14	Conventional
Los Prados-Málaga	4.318	50/14	Conventional

B.6 Routes

In this example there will be two routes, one for the Málaga-Fuengirola (C1), and the another one for Málaga-Alora (C2). Each of them will be introduced into the program by its graphic user interface, placing the initial node and the final one, taking into account the lines previously defined. Each route will be done for one way trip and one way back, separately. Fig. B-3 shows as example the outward journey "Málaga-Fuengirola".

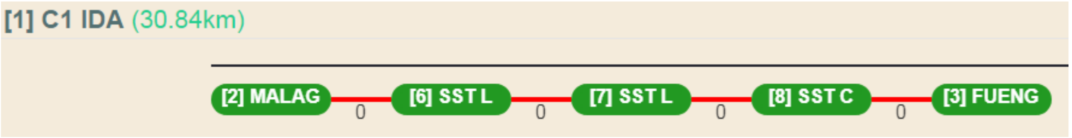


Figure B-3: Definition of a route in RailNeos 2.0.

B.7 XTP Profiles

In this part of the simulation, the XTP files obtained from the ITINER simulation must be included (see Appendix A), where each XTP is associated to a route. Note it necessary to introduce here are to introduce one for the outward journey and another for the return trip for each route.

B.8 Schedule

The final part for the simulation is to introduce the schedule with the departures of the trains. In this case, four train departure types will be existing, and they are summarized in Table B.4.

Table B.4: Schedule for the simulation

Route	1st departure	Time between dep.	Dep. times	Power scale
$C1_{IDA}$	19:00:00	20:00	6	100
$C1_{VUELTA}$	19:10:00	20:00	6	100
$C2_{IDA}$	19:40	1:00:00	2	100
$C2_{VUELTA}$	19:55	1:00:00	2	100

B.9 Simulation

In order to make any simulation, once the whole railway system is introduced, it is necessary to go to the “Simulación y análisis” (Spanish for simulation and analysis) tab, and then in simulation, the initial simulation time (in this case 19:00:00) and its duration are set. After the simulation is performed, the different parameters of the railway system can be studies (from the node behavior up to the train performance). For more information go to [38]. Fig. B-4 shows the network, that as it can be seen it is quite similar to the real one.

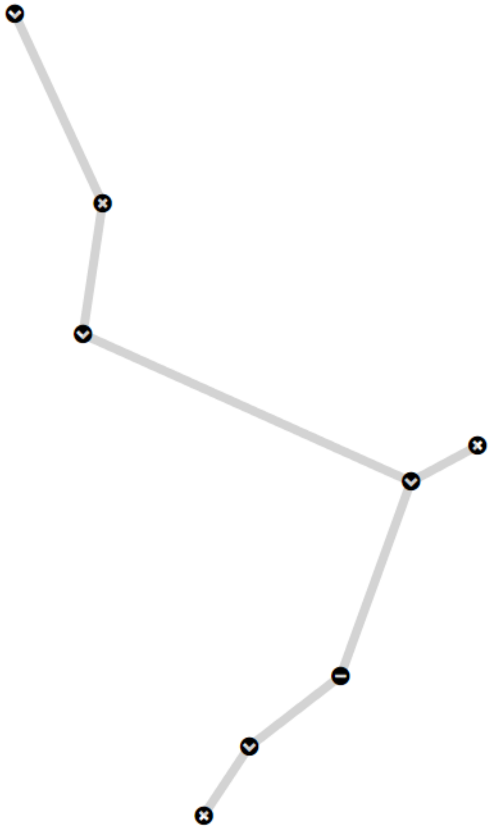


Figure B-4: Railway system in RailNeos 2.0.

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