Techno-economical analysis of DC railway traction networks: a methodology to optimally selected the system contracted power

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

In the present work, a real traction system operated under different scenarios and using different technologies is analysed. The analysis of the technical simulations providing electrical variables will be conjugated with optimization methods applied to the economic study of the network operation in order to extract the different factors that a higher correlation in the electrical variables as well as the operation cost. In particular, the work is focused on establishing a general method that allows the railway operator to properly select the electric tariff and its corresponding contracted capacity optimally so that the electricity bill is minimized. To do so, a previous implementation of a tool that calculates the electricity bill has been done.

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Chapter 1

Introduction

1.1 Background

There is no doubt on the general environmental concern and, in response, worldwide regulations are pishing to minimize green house emissions, specially in transportation. Huge efforts are being done to reduce the number of vehicles (of any kind) powered by fossil combustibles. Railway transport has been historically a main mode of transport for goods either for people. There are two main power system types for traction: the diesel and the electrified lines. Railway systems powered by diesel have been historically very popular due its low cost, operation simplicity and economic efficiency. Nevertheless, the current concern about the emissions is pushing the balance to the side of the electrified railway lines. The problem of pollution is even more remarkable in urban areas. Due to that fact the electrification of railway systems has not stopped to grow in the last decade.

Both from the environmental and the efficiency point of view electric trains are more interesting than diesel ones. However, the electrification of the infrastructure introduces a high level of complexity. The railway infrastructure can be compared to a conventional distribution network, but with special features. In this case, the rolling stock can be seen as the consumer (mobile loads) to supply, and the conventional electric AC grid as the power source of the system. Additionally, it must be taken into account that new concerns like controllability, capability, stability, communications, energy flows and so on are essential to control these systems in order to reach a feasible efficient and reliable system.

A wide range of feeding systems configurations can be found. There is not a unique or standardized solution, however, they can be divide in AC and DC networks. On the one hand there are DC grids at 600, 750, 1500 and 3000 V; and in the other hand there are AC network, which itself can be divided in low-frequency systems (16.7Hz, 20Hz and 25 Hz at voltage levels of generally 15kV) and industrial frequency systems (50 and 60 Hz at generally 25 kV). The voltage level is quite important regarding to the losses in the system (higher voltage imply lower current), which implies that the maximum distance between traction substations (TSS's) is quite higher for the case of AC systems (around 7.5 km) compared to the DC systems (around 2.5 km) [12]. A geographical distribution of railway feeding systems types review throughout Europe can be found in [13]. Despite the AC system advantages, it is remarkable that insulation problems are quite worse than in DC systems as well as the cost of these systems is generally higher than in the DC case. The present work is not focused in AC electrification despite that a considerable part of the railway infrastructure uses this technology.

Despite the technological developments in power electronics, railway manufacturers and operators have been historically quite conservative comparing to other industry sectors. This caused that the majority of urban networks use DC technologies with low voltage levels. Historically this decision was taken due to the lower insulation problems that these systems caused, as well as security issues since it shares space with pedestrians. Additionally, the converters used in feeding substations are mainly diode rectifiers of 6 or 12 pulses that do not allow the regeneration of energy into the catenary. A DC traction substation scheme is shown in Fig. 1-1. Lastly, the parallel connection of IGBT converters has started to be introduced in order to have a better energy management. Not only the improvements in power electronics are remarkable, but also the introduction of accumulation systems took place at substations and on-board systems.

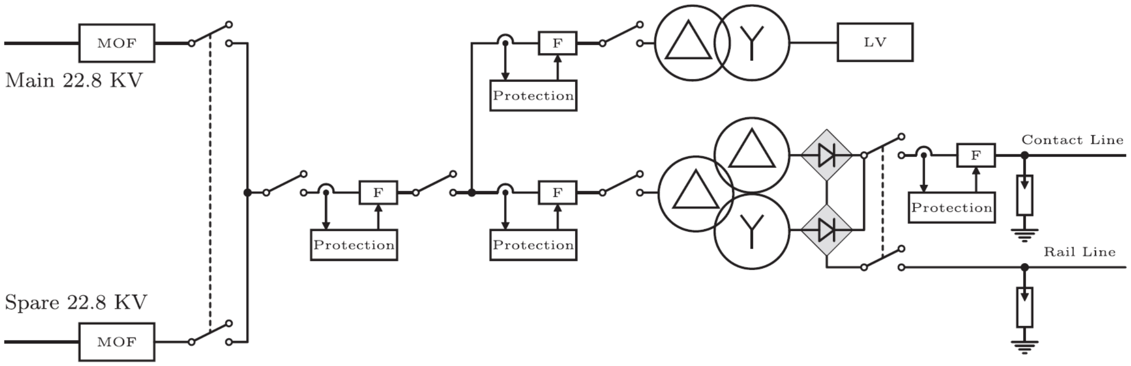


Figure 1-1: Real scheme of a DC traction substation [1].

1.2 Literature review

In the same way that technology was developed, the simulators and planning tools for railway systems also evolved. These new tools had to, on the one hand, to include mathematical models of new technologies as they appear as well as adapting the solving algorithms of the power system. On the other hand, with the increase of traffic in railway networks, the operators had to improve their planning techniques. Additionally, as in most of electric industries, nowadays the power quality became a central topic and thus, the impact on the AC grid should be reduced.

As previously introduced, the railway power systems have very specific characteristics, which causes that in comparison with conventional distribution systems, the number of companies in the market is really reduced. As a consequence, the number of simulation and planning tools is quite limited. Actually, many manufacturers and operators developed their own simulators. It is complicated to find integrated solutions in the market that include the simulation of the rolling stock as well as the feeding system. The majority of the tools are focused in one of these two parts. In [1], the main commercial softwares are analysed.

Due to the above mentioned, the majority of research efforts are focused on three lines:

- Development of static mathematical models and solvers: this approach generally uses power flow algorithms as an analysis tool. It is used mainly for planning and operation purposes. It is divided in decoupled approaches, where the rolling stock and infrastructure are considered independently, and in integrated approaches, where trains and infrastructure are included in the same simulation framework.

The first approach is suitable for the sizing of the infrastructure and its electric performance, as well as to evaluate the impact of different technologies such as energy storage systems. Conversely, for the train management and network planning it is required the integrated solution.

- Development of dynamic mathematical models and solvers: very detailed models are used, which limits the simulation intervals. This approach is generally used to evaluate very specific scenarios, mainly regarding to power quality issues. The dynamic simulations are very diverse, it goes from specific parts of the system to the whole system with or without considering the rolling stock. Here, specific modelling techniques such as small signal or Energetic Macroscopic Representation (EMR) are used among others.
- Specific cases of use of different simulation tools and models: due to the growing complexity of the systems, the variety of the technological solutions and the increase of competitors, it has become essential to perform not only accurate technical solutions, but also the achievement of cost efficient systems. Due to that, existing simulators are being developed in that line as well as new research lines based on optimizations to improve the final efficiency of the system are arising. However, the optimizers require from higher computational resources since they use more complex mathematical techniques such as genetic algorithms or hardware in the loop.

Railway systems are extraordinarily complex and multidisciplinary. That leads that over the year totally different research lines focused on its improvements. Big efforts have been done along the last decades to developed more efficient technologies that help to minimize the energy demand of the system as well as to take the maximum profit of it with techniques such as the regenerative braking or the add of energy storage systems. In [2] a detailed comparison of the impact on the network of the different technologies both for the feeding infrastructure and the rolling stock can be found.

Nevertheless, if those technological improvements are not conjugated with optimal software development to achieve an optimal management of the same, the benefits obtained will be much more limited that the ones that could be achieved. In this regard, railway operators started to give a big focus on energetic studies assessment as well as on the optimal operation of the network.

Because of the interrelationship that exists between the aim pursued by the present work and the optimizers, a special attention has been paid them to give an overview of the existent work as well as to present its benefits and limitations.

Only looking to the works that make energetic studies, there is an extensive variety of approaches for planning and operation purposes, which goes from driving management optimisation to train timetables optimization or optimal infrastructure sizing to minimize the system losses. In [1] an extent list of these works can be found, which are classified in three main topics: trajectory and schedule optimisation, infrastructure optimisation, and energy management and control.

Complex but detailed and clear approaches of schedule optimisation can be found in [7] and [8]. These approaches are based on optimizing the train timetables in such a way that a series of optimal coupling relationships among trains are generated. The obtained results claim that utilization ratio of regenerative braking energy by optimizing the timetable can raise up tp a 80%. Nonetheless, it is important to remark that these results are subject to the compliance of certain constraints such as the headway or dwelling time constraints, which in reality are much less flexible from the ones selected to solve the problem. For example, the headway constraints is selected as quite flexible factor, however, in practical operations that is not possible due to the fact that generally the headway is configured in such a way that it is quite easy to remember for the costumers (i.e. each 10 minutes), and it cannot be changed with each trip. Moreover, the headway determines the transportation capacity and thus, there are always upper and lower limits on the headway (there must be the same hours of operation every day and within a same time range).

There are several works focused on the optimal placing and sizing of the feeding substation with and without considering different technologies [6, 4, 10]. Similarly to the exposed in the previous case, in real operation, specially in urban areas, usually the feeding substation will not be placed in the optimal place to reduce the losses, but where it is possible.

In conclusion, the results obtained by means of optimizers are excellent, however, it is important to remark that these achievements up to the moment are only valid in research. Optimization problems are extremely complex mathematical problems. Its computational time and resolution difficulty are strongly related to the number of stated constraints and their type, which makes not so feasible to incorporate them in the daily work of the railway companies.

1.3 Motivations

An essential part of competitiveness is the reduction of costs. In this regard, large users of electricity resources such as railway operators have the complex target of minimizing the electricity bill by means of technological improvements and optimal operation planning and management.

As briefly introduced above, there are many research lines to cover such a multidisciplinary industry as they are the traction systems, in which lately big efforts have been done to develop optimal methods to reduce the energy demand with the increase of traffic densities. These optimization tools are expected to bring many benefits to reduce costs in different aspects of the system. However, its application in real systems still not a reality.

Due to the limitations and specialization needed to implement optimization algorithms, it has been proposed to define a method for optimizing the electricity tariff and its corresponding contracted powers in order to minimize the cost of the electricity bill in a simple way. This method is general for any railway system, it is simple and considers all the different scenarios that must be evaluated in a railway network such as the different traffics densities present, possible failures in the feeding substations or the possibility of adding accumulation systems. Additionally, it does not require any specific software or commercial tool to be carried out.

1.4 Thesis structure

This Master's Thesis is divided in four chapters, being each of them focused on the following:

- Chapter 1: In this chapter, a introduction on the railway systems background is done as well as brief overview of the main research topics related to railway traction systems is performed. Special attention is paid to the optimization tools research line. Additionally, the main goals of the project are presented.
- Chapter 2: Here, a brief introduction to the simulation programs used by CAF TE to perform the infrastructure design is done. Furthermore, the railway network, devices and train models are shortly described.
- Chapter 3: The focus of this chapter is on the implementation of a tool to obtain the operating costs of a railway network given its consumptions. In a first part, the theoretical formulation imposed by Spanish regulations is detailed. Subsequently, its implementation and validation in *MatLab* is detailed.
- Chapter 4: In this chapter, a railway real network in the south of Spain is presented and characterized. Following to that, a methodology to selected the optimal contracted capacity for this type of systems is deeply developed. Moreover, the method conclusion are validated with a commercial optimization tool of *MatLab*. Finally, the cost impact on the electricity bill of adding energy storage systems both off-board and on-board is evaluated.
- Chapter 5: Finally, in this chapter a summarize of the main conclusion regarding the topic are extracted as well as some future improvements are commented.

Chapter 2

Simulation Tools

2.1 ITINER

Nowadays, one of the main concerns of society is the need to preserve the environment, reduce greenhouse gas emissions and achieve sustainable development. Within the need to provide various solutions that further respect the environment, the railway sector works in line with reducing the consumption generated by vehicles.

To reduce as maximum as possible the energy consumption or in other words to make the whole systems as efficient as possible has open many research lines in the railway field from technology improvements to algorithms for train schedule optimization or control driving management.

It has such importance to reduce the energy consumption that customers are currently including consumption limitations in their specifications and even more, in some cases they include penalizations if the real operation consumption does not match with the one specified in the offer. For this reason, in order to remain competitive in the market, vehicle manufacturers such as the CAF group are not only forced to optimize their vehicle energy and thus continuously improve its efficiency, but they also have to calculate energy consumption correctly and accurately.

In order to predict the total energy consumed by the system there are several factors which affect it, among them the resistance to advance, the driving management, optimal management of the auxiliaries and the performance of the equipment (specially the traction part). Nevertheless, these total consumption predictions are also affected by the accuracy of the train modelling, the track data, the maximum service time and the route to be taken.

This was the main aim which motivated to CAF for developing ITINER. This is a simulation tool for simulating rail routes and computing the consumption of their rail vehicles. It allows to generate train models and simulate their dynamic and electric behaviour for certain route in order to know the vehicle consumption in an accurate manner, by introducing efficient driving strategies and meeting the time objectives that the operator generally sets in a given infrastructure. These simulations are independent from the feeding type, being indifferent if it is an AC or DC supply.

The main feature of ITINER is that it is based on the resolution of analytical equations, which allow determining the increment of time and space necessary to go from a known initial speed to a final speed also known. The calculation is made by applying the maximum available traction or brake effort according to the vehicle's performance.

The general structure of the simulation tool ITINER is divided in three steps: the pre-processing or data input, the simulation and the post-processing.

2.1.1 Input data

The input data step is where all variables are assigned to the different input data. The main features to define are related to the vehicle, the track and the driving type. Some of these variables will be a function of the 'kilometer point (KP)' of the track.

Therefore, the input data is defined in three different files:

- File simulation: here is introduced all the information regarding to the scenario to be analysed as well as the simulation setting (such as the simulation time).

- File track:this file contains all the information about the track/route (vertical and horizontal profiles, substations location, speed limits, tunnels, timetables, etc).

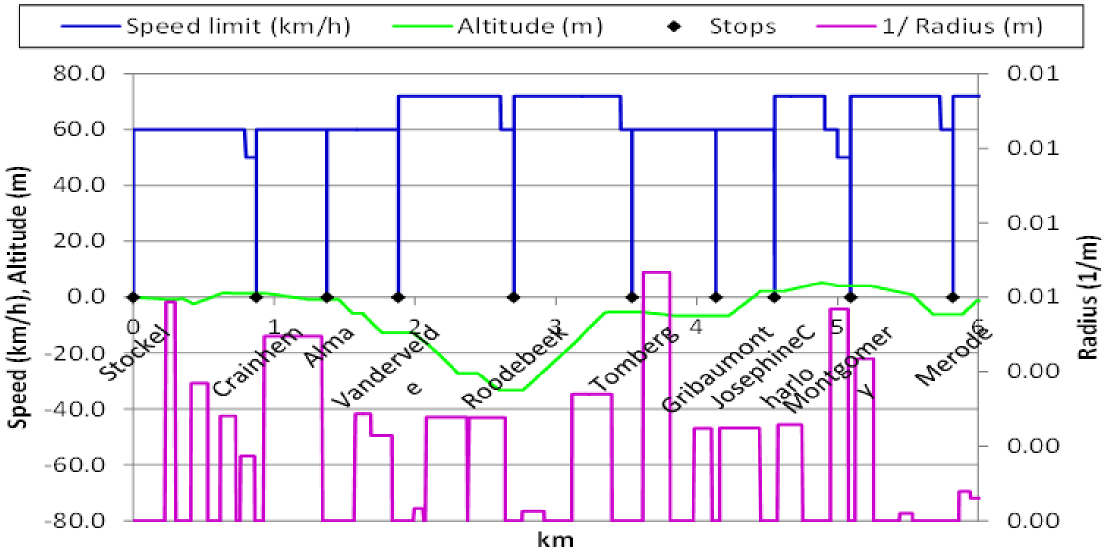


Figure 2-1: Example of ITINER input data of 'track & operational parameters' to compute the speed profile module.

- File vehicle: in this file all the general characteristics of the vehicle are set (wheel radius, weight, etc).

ITINER will use these vehicle parameters to compute the energy required at the wheels (mechanical energy) taking into account the time limitations for the defined track.

2.1.2 Simulation

In this process the speed profile is computed along the defined track by the application (*Matlab* based).

This tool allows to modify some of the variables such as the driving management, the maximum braking speed, the electric brake and so on in order to fit the speed profile.

2.1.3 Post-processing

Once the speed profile is obtained, there is the option to do a post-processing, which is compound by two parts:

1. The results are depicted in terms of the time and speed (see Fig. 2-2).

2. The consumption of the train and the losses in the traction chain are computed (see Fig. 2-3 and 2-4).

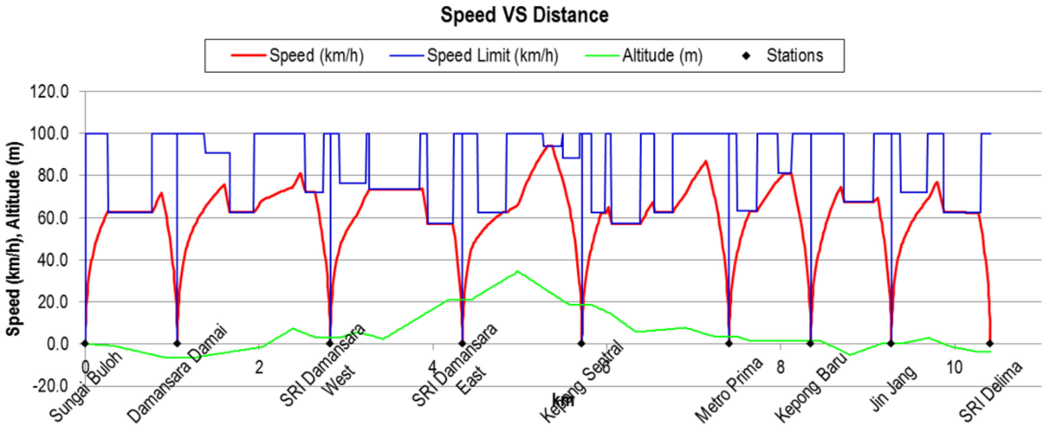


Figure 2-2: Example of an speed profile obtained with ITINER with an ’all-out’ driving mode.

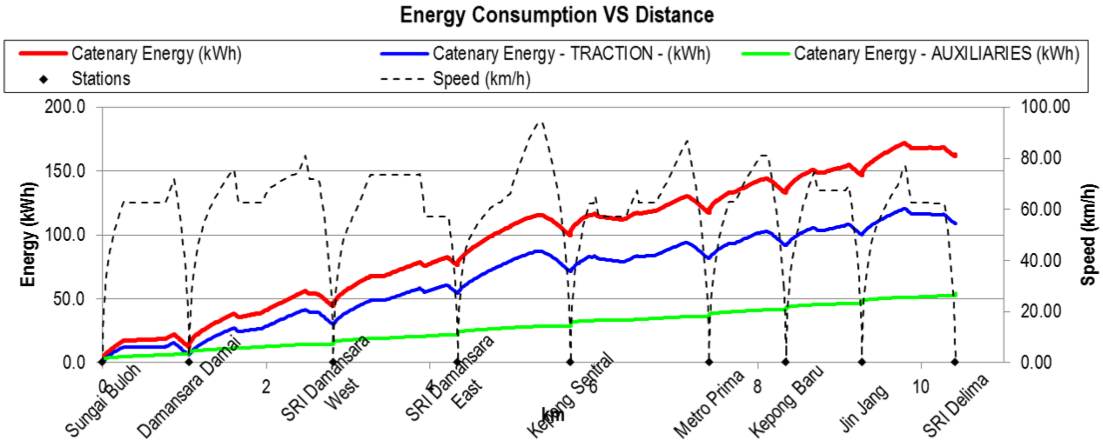


Figure 2-3: Example of energy consumptions obtained with ITINER.

The energy consumption of the train will be used for extracting the XTP (position-time-power) file, which is used later as the input for RailNeos simulation tool.

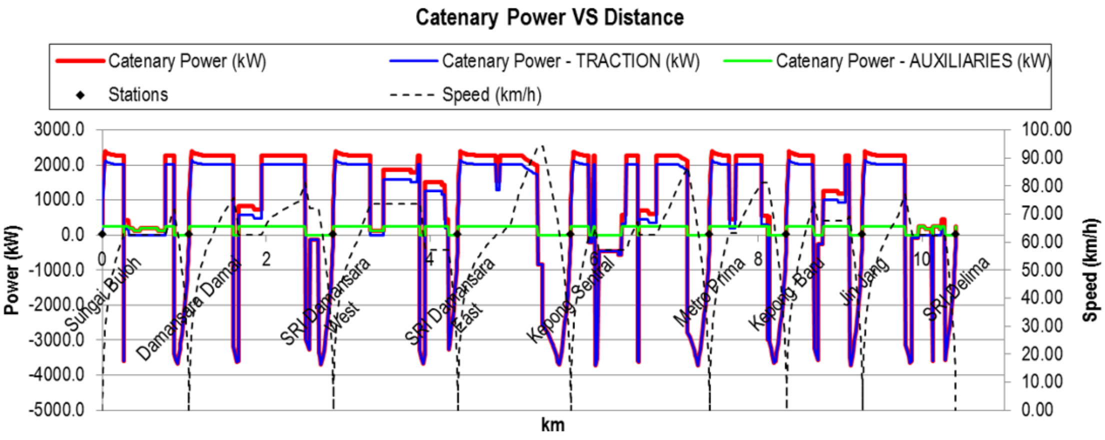


Figure 2-4: Example of power consumptions obtained with ITINER.

2.2 RailNeos 3.0

RailNeos 3.0 is a web tool simulator developed between CAF Turnkey & Engineering (CAF TE) and the University of Oviedo within the ESTEFI project.

Many elements have to be considered so as to electrify a track stretch of several kilometres in length. Sizing electric railway systems requires a long process in which many calculation and variables are involved due to that great amount of devices that are present in these systems as well as due to the fact that loads continuously change their position in time.

Therefore, simulators are excellent tools to face new engineering problems, testing different prototypes to develop optimal designs in an easy, fast and economic manner.

This software allows to calculate the energy consumption from different substations within a certain track as well as other many variables such as the voltage profile along the whole line, currents, active and reactive power, losses and so on, taking into account mix-mode substations and energy storage systems (ESS), either on-board or track-side.

The results are shown in an interactive web interface (see Fig. 2-5) that is able to represent all the electric variables, with the purpose of understanding the behaviour of the network and allowing to design the most efficient topology of the system.

In order to carry out simulations with RailNeos it is necessary to have been

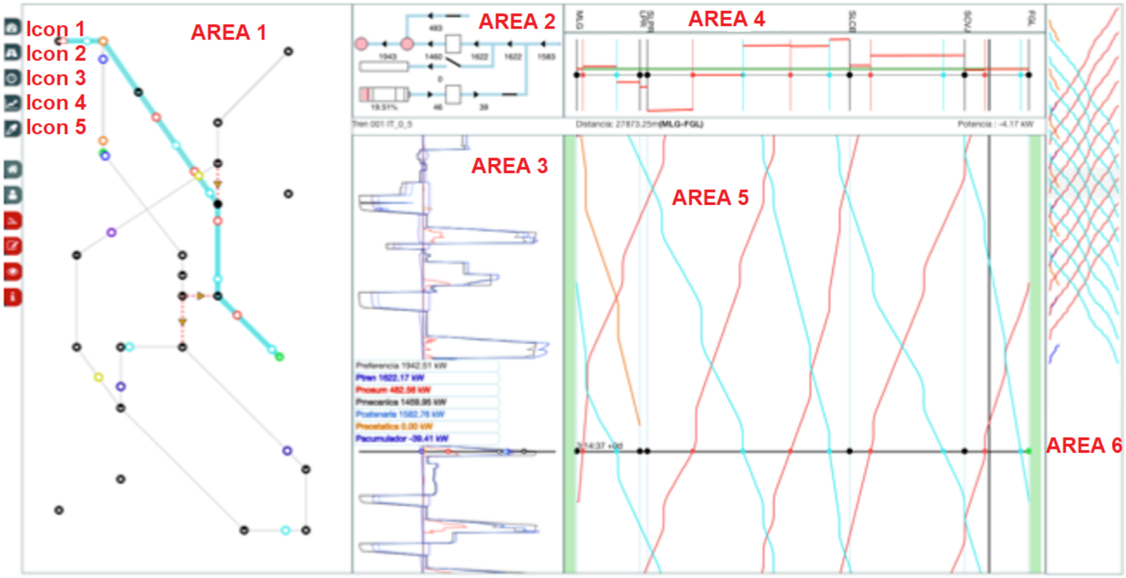


Figure 2-5: RailNeos simulation and analysis screen.

previously done a simulation based on rolling stock with the aforementioned simulation program ITINER to obtain the XTP file, whose results are introduced in RailNeos as input as well as the electrical infrastructure characteristics of the system, the different trajectories and the different operating times. Take into consideration that there are other input files very similar to the XTP file, which include information of loads connected to nodes (TP) and the buses recharging point (XT) if applies.

RailNeos 3.0 is a tool that can be used for analysing the planning operations and the most convenient schedules for the vehicles. In addition, it can serve as support tool to reduce the operational cost and it is possible to evaluate the techno-economic impact of the implementation of different technologies such as the use of ESS, on-board or off-board and their size or reversible substations.

The results will be exported in a database that will be the data input of the post-processing module, which can be also exported in a database form.

2.2.1 Simulation configuration

In order to define a new network, as above mentioned, it is necessary to set the infrastructure characteristics as following is briefly presented.

1. Configuration: Here the base power of the system is defined. This base will be common to all the elements and levels of voltage.

2. Base voltage: In this field, all the base voltages necessary to define the system are defined (i.e. 750 V and 3000 V) and, moreover, in this field there is the possibility of defining an access rate (3 and 6 rates) and a power contracted for each of the three- or six-periods in order to later compute the post-processing module and obtain the operation cost of the system.

   The user has the possibility of defining access electricity rates as well as their corresponding contracted powers for each of the nodes in the network. If this is the case, it will be required to define as many base voltages as different access rate configurations were needed.

   Finally, there is also the possibility of uploading four csv (comma-separated-values) files: a file to define the active power prices ($Price\_P$), a file to define the active energy price ($Price\_E$), a file to define the time periods for 3-rates ($Timing\_1$) and a file to define the time periods for 6-rates ($Timing\_2$). All of this data is regulated by the Spanish government and it will be explained in detail in Section 3.

3. Nodes: A node is broadly defined as a network element to which a train line, bus line, or link can be connected. In turn, the node may or may not be connected to the AC network through a substation. There are different types of substations: disconnected from the AC side (type 0), bidirectional (type 1), bidirectional with deadband (type 2), unidirectional with or without deadband (type 3).

   Therefore, in this field, there is defined the node general characteristics (name, type, coordenates,...) as well as its electrical characteristics (base voltage, impedances,...).

   In Fig. 2-6, the general model of a node can be seen, the part on the right represents the AC part, while the part on the left represents the DC part in which the accumulator, the current drain for the specular load and the connection to the traction network itself. Accumulators at the substation level are always associated with a node, although they are defined independently in another section.

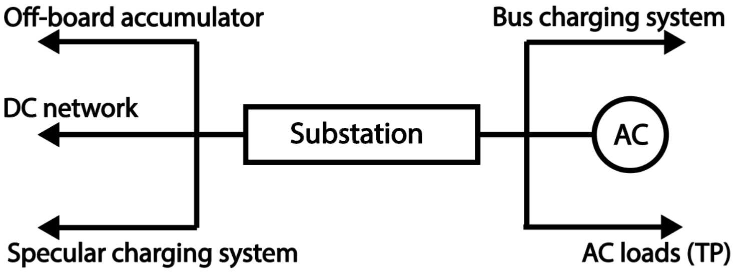


Figure 2-6: Simplified node model representation. [9]

Commonly, railway system have non-reversible substations which are equipped with a non-controlled diode rectifier. If the reversibility characteristic is required a controlled IGBT based converter is connected in parallel as shown in Fig. 2-7. Therefore, the substation characteristic will depend on the selected type. The power injection from the AC side into the DC side is represented by the forward resistance (Rf) and when the substation is inversely polarized beyond a predetermined parameter (Vr), the reverse IGBT branch is activated and the substation behaves as a resistance (Rr) injecting reverse power into the AC system. Therefore, in the case of a unidirectional substation, the reverse resistance (Rr) is set to 'infinite'.

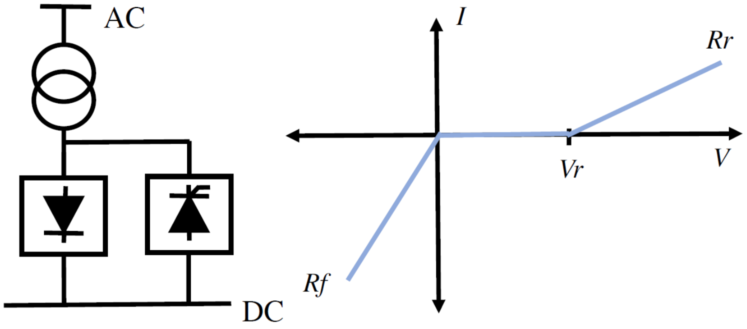


Figure 2-7: Simplified substation model representation. [2]

4. Train model: A train model is defined according to its efficiency in traction and braking mode and the curves that define the protection against overcurrent at low voltage and against overvoltage in catenary. Later, with one train model can be generated as many trains as required.

   A train may have an on-board accumulation system, but the accumulation systems will be defined independently and associated with a specific train model.

   The mathematical model of the train plus the accumulator is represented in Fig. 2-8. The traction behaviour along the overcurrent and deep discharge curves (on the left part of the figure) can be seen in Fig. 2-8 and, in the same manner, the overvoltage and overcharge curves for braking mode are represented in the lower part of the figure.

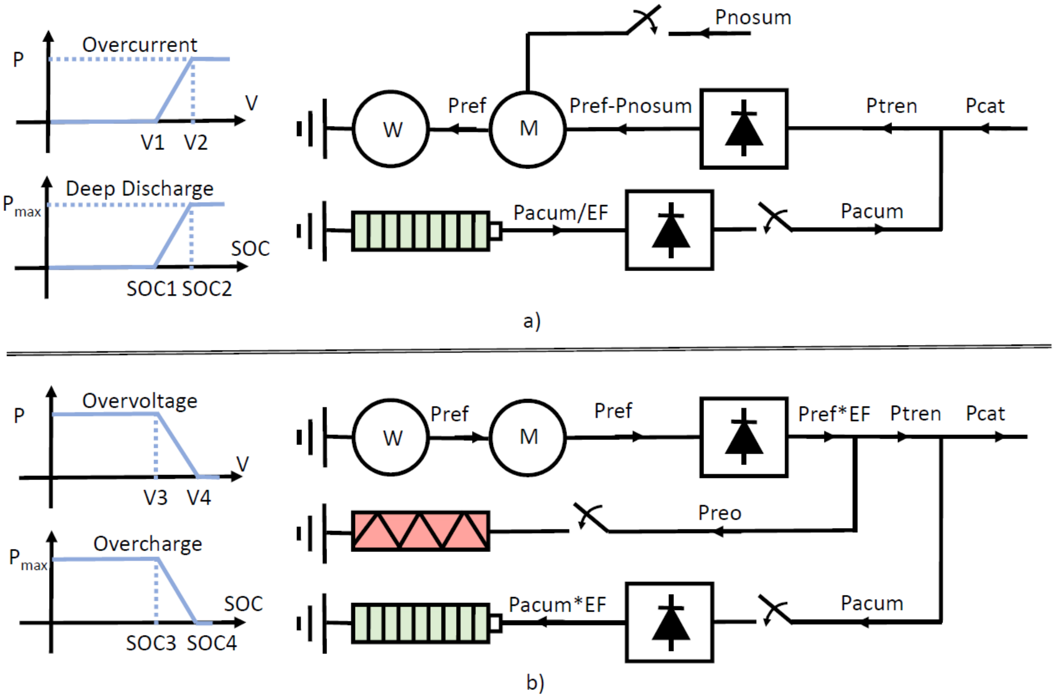


Figure 2-8: Simplified train model representation. a) Train in traction mode. b) Train in braking mode. W stands for the wheels set and M represents the traction motor system. [2]

5. Buses: To define a bus it is only required one parameter, which is the power that the bus will demand from a recharging node when it is stopped on that node.

6. Energy storage: In this section, all accumulation systems will be defined, on-board or at the substation level.
   - On-board energy storage systems (ESST): By automatically defining a train an associated on-board accumulation system is generated, so that each defined train model will have its own accumulator model. that can later be enabled or not. If so, its general parameters must be defined (see Fig. 2-8): maximum energy, maximum charge and discharge power, initial charge (SOC), charge and discharge efficiency and the charge and discharge power-SOC curve.
   - Off-board energy storage systems (EESN): As in the previous case, when a node is generated, the accumulator associated with the node is automatically generated, which may or may not be enabled. The parameters to be defined will be the same that in the previous case (see Fig. 2-9).

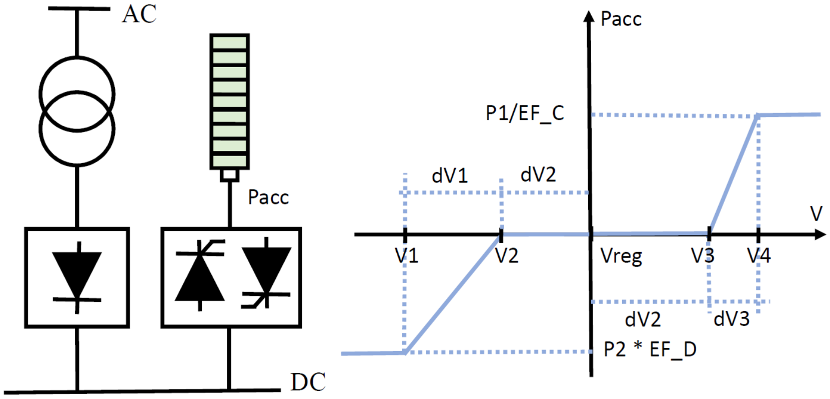


Figure 2-9: Simplified off-board accumulator model representation. [2]

7. Lines: This section is divided into two subsections, "Train lines" will describe the connections between nodes between which a train can drive along, while the subsection "bus lines" will describe the connections between nodes between which a bus can drive along.

8. Links: They are electrical connections through converters between nodes of the same base voltage or different base voltages.

9. Tracks: Both train and bus routes are defined in this field. To generate a route, it has to be selected the outbound node (from) and the arrival node (to) and an atomically line will be created, also the track length must be defined and it should coincide with the XTP file. In Fig. 2-10, it can be seen an example of a train track definition.

[1] MLG-FGL (30.84km)
[6] MLG 0 [5] LPR 0 [4] SLPR 0 [3] SLCB 0 [2] SCVJ 0 [1] FGL

[2] FGL-MLG (30.84km)
[1] FGL 0 [2] SCVJ 0 [3] SLCB 0 [4] SLPR 0 [5] LPR 0 [6] MLG

[3] MLG-ALR (36.93km)
[6] MLG 0 [5] LPR 0 [7] SPZR 0 [8] ALR

[4] ALR-MLG (36.94km)
[8] ALR 0 [7] SPZR 0 [5] LPR 0 [6] MLG

Figure 2-10: General edition screen of train routes.

10. Profiles: In this section the XTP files corresponding to the trains are selected and associated with a train track, the XT files corresponding to the buses are associated with a bus track. There is also the possibility to upload TP files corresponding to a load/charging point on a node.

11. Schedules: This section allows to define the trains and buses operating time (schedule) and if required it is possible to set the times in which the loads connected to the AC of the substations are connected.

2.2.2 General structure of the generated networks

As previously introduced, any generated network can be download (once it is been simulated) from the interface and it will contain three database files (see Fig. 2-11):

1. *net.db*: Database containing the description of the network, trains, schedules, accumulation systems, links, substations and other elements necessary to launch the simulation. In this database there will be 20 tables.

2. *res.db*: Database with the output results in which the input data is also duplicated. In this case there are 29 tables, 20 of which are common with net.db and the remaining 9 collect the output data. The tables that collect the simulation output data all start with the word "OUT".

3. *post.db*: Database containing the post-processing results. It takes the results database (res.db) as input. In this case there are 8 tables where the aggregated data of the system, the substations and the trains are represented. The post-processing signals are divided in three types of signals:

   o $< SignalName >$ _ Net: sum of all the signal values.

   o $< SignalName >$ _ In: absolute sum of the negative values of the signal.

   o $< SignalName >$ _ Out: absolute sum of the positive values of the signal.

   That is the post-processing returns signals of net, demanded and generated aggregated energy.

In order to communicate with the data bases SQL (Structured Query Language) is employed. In this work the free software SQLite has been used.

In the present work not all the variables and tables will be defined, but a review of the ones that have been used to develop the economic module will be following shortly presented:

1. Table *Cfg*: it defines the network configuration and it is defined by thirteen variables as can be seen in Fig. 2-12.

   - ID: Identification of the network, it is automatically generated.
   - Base_P: Base power in MVA.

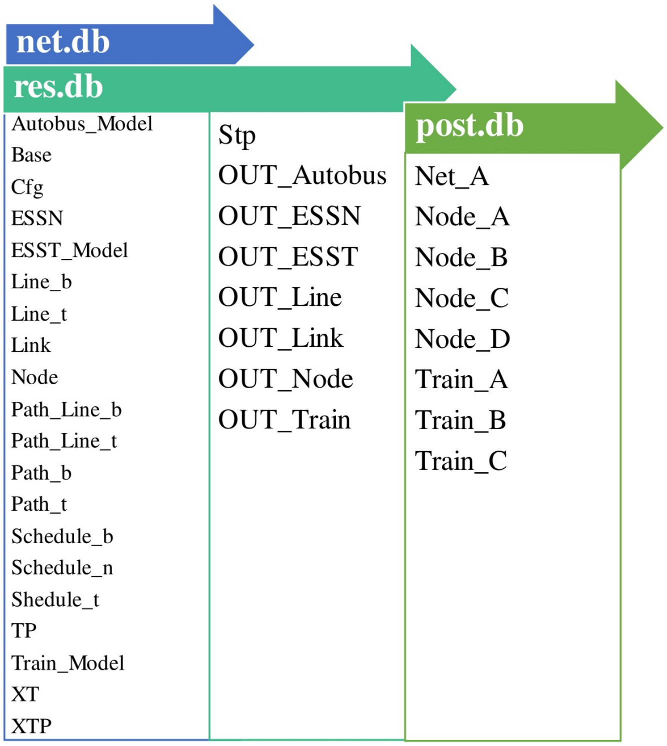


Figure 2-11: Database general structure scheme.

Tabla: Cfg

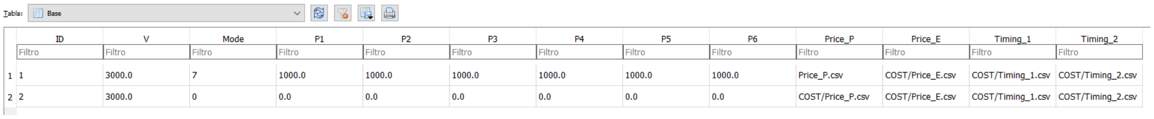
	ID	Base_P	Min_R	V_Digits	Max_Try	Mode	Start_Time	Sim_Time	Sample_Time	Opt1	Opt2	Opt3	Opt4
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	1	1.0	1.0	5	1000	1	19800.0	66600.0	1.0	0.1	1.0	0.0	0.0

Figure 2-12: Network configuration model in the database.

- Min_R: Minimum resistance in mOhm that can exist between any two devices. If the resistance is lower than that, the models are merged and solved as a single model.
- V_Digits: Number of digits used for voltages in the p.u (per unit) system.
- Max_Try: Maximum number of iterations allowed to solve a specific instant.
- Mode: 0 Resolution of a single instant. 1 Resolution of an interval of simulation instants.
- Start_Time: Start time of the simulation in seconds.
- Sim_Time: Duration of the simulation in seconds.
- Sample_Time: Simulation frequency in seconds.

  - Opt1, Opt2, Opt3, Opt4: Configuration parameters of the DCTS calculation engine, must be configured with the values 0.1, 1.0, 0.0, 0.0.

2. Table *Base*: Base voltages of the different areas present in the simulation. It is defined by thirteen variables as can be seen in Fig. 2-13.



	ID	V	Mode	P1	P2	P3	P4	P5	P6	Price_P	Price_E	Timing_1	Timing_2
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	1	3000.0	7	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	Price_P.csv	COST/Price_E.csv	COST/Timing_1.csv	COST/Timing_2.csv
2	2	3000.0	0	0.0	0.0	0.0	0.0	0.0	0.0	COST/Price_P.csv	COST/Price_E.csv	COST/Timing_1.csv	COST/Timing_2.csv

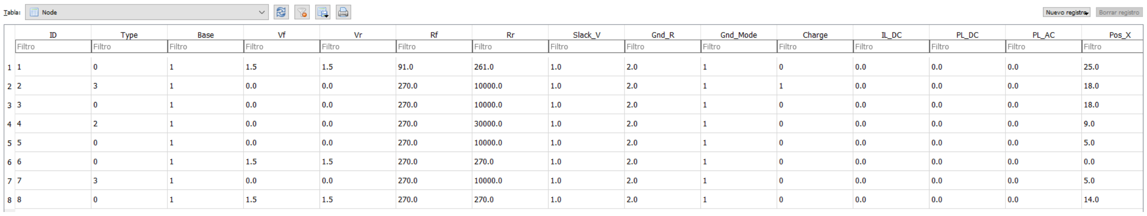
Figure 2-13: Base voltages model in the database.

  - ID: Identifier of the base voltage, it is automatically generated.
  - V: Value of the base voltage in Volts.
  - Mode: Represent the selected electricity tariff. 0→OFF, 1→3.0, 2→3.1, 3→6.1, 4→6.2, 5→6.3, 6→6.4, 7→6.5. *If the option 'OFF' is selected the post-processing calculation to compute the cost will not be done for the node in which that base voltage is configured.*
  - P1, P2, P3, P4, P5, P6: are the contracted power defined for periods 1 to 6.
  - Price_P: csv file used to define the active power prices.
  - Price_E: csv file used to define the active energy prices.
  - Timing_1: csv file used to define the time discrimination for 3-rates.
  - Timing_2: csv file used to define the time discrimination for 6-rates.

   All the files employed to compute the operation cost will be in a folder called 'COST' given when the results of a simulated network are downloaded.

3. Table *Node*: It contains the data related to the nodes. It is defined by seventeen variables as can be seen in Fig. 2-14.

  - ID: Identifier of the node.



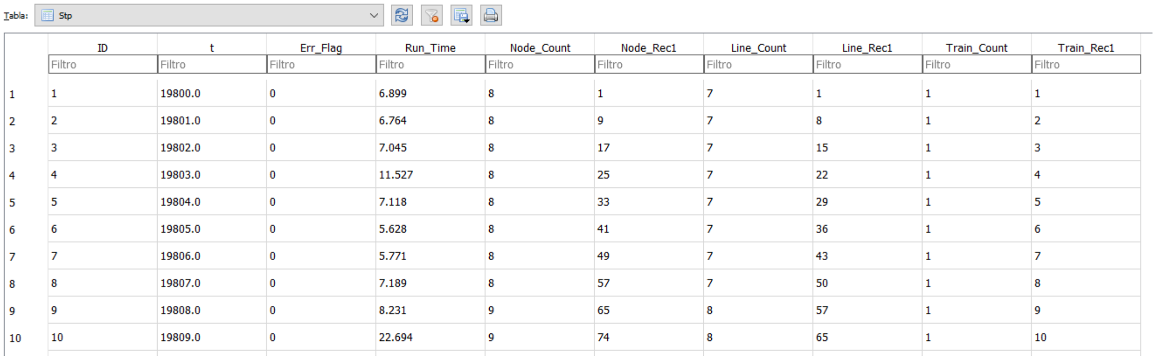
	ID	Type	Base	Vf	Vr	Rf	Rr	Slack_V	Gnd_R	Gnd_Mode	Charge	IL_DC	PL_DC	PL_AC	Pos_X
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	1	0	1	1.5	1.5	91.0	261.0	1.0	2.0	1	0	0.0	0.0	0.0	25.0
2	2	3	1	0.0	0.0	270.0	10000.0	1.0	2.0	1	1	0.0	0.0	0.0	18.0
3	3	0	1	0.0	0.0	270.0	10000.0	1.0	2.0	1	0	0.0	0.0	0.0	18.0
4	4	2	1	0.0	0.0	270.0	30000.0	1.0	2.0	1	0	0.0	0.0	0.0	9.0
5	5	0	1	0.0	0.0	270.0	10000.0	1.0	2.0	1	0	0.0	0.0	0.0	5.0
6	6	0	1	1.5	1.5	270.0	270.0	1.0	2.0	1	0	0.0	0.0	0.0	0.0
7	7	3	1	0.0	0.0	270.0	10000.0	1.0	2.0	1	0	0.0	0.0	0.0	5.0
8	8	0	1	1.5	1.5	270.0	270.0	1.0	2.0	1	0	0.0	0.0	0.0	14.0

Figure 2-14: Node model in the database.

- Type: Node Type. 0: Disconnected, 1: Bidirectional, 2: Bidirectional with deadband, 3: Unidirectional.
- Base: Base voltage of the DC part of the node, the train lines will only be able to connect nodes with the same base voltage.
- Vf: Voltage for the deadband of branch f (forward).
- Vr: Voltage for the deadband of the branch r (reverse).
- Rf: Resistance of the branch f of the link.
- Rr: Resistance of the branch r of the link.
- Slack_V: Adjustment of the supply voltage of the distributed slack that feeds the node, defined in p.u. 1pu means that the voltage in the DC side will be the base voltage assigned to the node when the substation is in no-load conditions.
- Gnd_R: Ground impedance in the continuous part of the substation in Ohms.
- Gnd_Mode: Substation grounding enabled (1) or disabled (0).
- Charge: Recharging of electric buses enabled (1) or disabled (0).
- IL_DC: Constant drainage current in the DC part for specular load in A.
- PL_DC: Constant drainage power in kW in the DC part.
- PL_AC: Constant drainage power in kW in the AC part.
- Pos_X: X coordinate of the node.
- Pos_Y: Y coordinate of the node.

    - Name: Name of the node.

4. Table *Stp*: It contains the general information of the solved cases. It is defined by ten variables as can be seen in Fig. 2-15

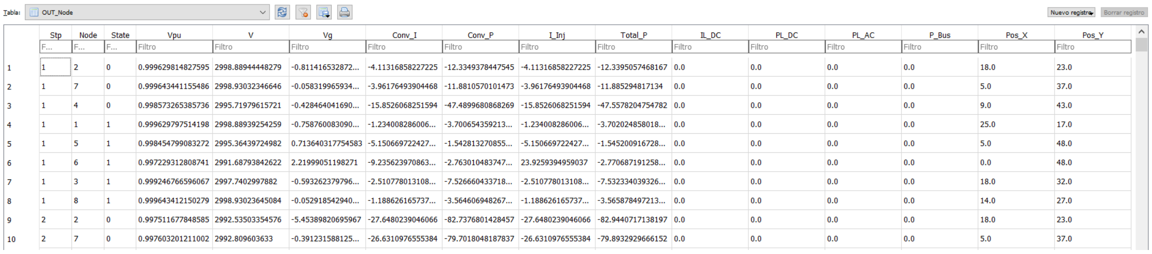


	ID	t	Err_Flag	Run_Time	Node_Count	Node_Rec1	Line_Count	Line_Rec1	Train_Count	Train_Rec1
	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	1	19800.0	0	6.899	8	1	7	1	1	1
2	2	19801.0	0	6.764	8	9	7	8	1	2
3	3	19802.0	0	7.045	8	17	7	15	1	3
4	4	19803.0	0	11.527	8	25	7	22	1	4
5	5	19804.0	0	7.118	8	33	7	29	1	5
6	6	19805.0	0	5.628	8	41	7	36	1	6
7	7	19806.0	0	5.771	8	49	7	43	1	7
8	8	19807.0	0	7.189	8	57	7	50	1	8
9	9	19808.0	0	8.231	9	65	8	57	1	9
10	10	19809.0	0	22.694	9	74	8	65	1	10

Figure 2-15: Departures register model in the database.

    - ID: Unique identifier for each instant resolved.
    - t: Time corresponding to the instant solved in seconds from the first instant resolved. The first instant resolved is zero, from there it assigns integer instants.
    - Err_Flag: 0: Convergence achieved. 1: Error, the solution could not be found.
    - Run_Time: Time spent solving the instant in milliseconds.
    - Node_Count: Total number of active nodes at the specific moment.
    - Node_Rec1: Position of the first record of the nodes corresponding to this moment in the general results table.
    - Line_Count: Total number of active lines at the specific moment.
    - Line_Rec1: Position of the first record of the lines corresponding to this moment in the general results table.
    - Train_Count: Total number of active trains at the specific moment.
    - Train_Rec1: Position of the first record of the trains corresponding to this moment in the general results table.

5. Table *OUT_Node*: Results corresponding to the nodes. It is defined by sixteen variables as can be seen in Fig. 2-16.



	Stp	Node	State	Vpu	V	Vg	Conv_I	Conv_P	I_Inj	Total_P	IL_DC	PL_DC	PL_AC	P_Bus	Pos_X	Pos_Y
	F...	F...	F...	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
1	1	2	0	0.999629814827595	2998.88944448279	-0.811416532872...	-4.11316858227225	-12.3349378447545	-4.11316858227225	-12.3395057468167	0.0	0.0	0.0	0.0	18.0	23.0
2	1	7	0	0.999643441155486	2998.93032346646	-0.058319965934...	-3.96176493904468	-11.8810570101473	-3.96176493904468	-11.885294817134	0.0	0.0	0.0	0.0	5.0	37.0
3	1	4	0	0.998573265385736	2995.71979615721	-0.428464041690...	-15.8526068251594	-47.4899680868269	-15.8526068251594	-47.5578204754782	0.0	0.0	0.0	0.0	9.0	43.0
4	1	1	1	0.999629797514198	2998.88939254259	-0.758760083090...	-1.234008286006...	-3.700654359213...	-1.234008286006...	-3.702024858018...	0.0	0.0	0.0	0.0	25.0	17.0
5	1	5	1	0.998454799083272	2995.36439724982	0.713640317754583	-5.150669722427...	-1.542813270855...	-5.150669722427...	-1.545200916728...	0.0	0.0	0.0	0.0	5.0	48.0
6	1	6	1	0.997229312808741	2991.68793842622	2.21999051198271	-9.235623970863...	-2.763010483747...	23.9259394959037	-2.770687191258...	0.0	0.0	0.0	0.0	0.0	48.0
7	1	3	1	0.999246766596067	2997.7402997882	-0.593262379796...	-2.510778013108...	-7.526660433718...	-2.510778013108...	-7.532334039326...	0.0	0.0	0.0	0.0	18.0	32.0
8	1	8	1	0.999643412150279	2998.93023645084	-0.052918542940...	-1.188626165737...	-3.564606948267...	-1.188626165737...	-3.565878497213...	0.0	0.0	0.0	0.0	14.0	27.0
9	2	2	0	0.997511677848585	2992.53503354576	-5.45389820695967	-27.6480239046066	-82.7376801428457	-27.6480239046066	-82.9440717138197	0.0	0.0	0.0	0.0	18.0	23.0
10	2	7	0	0.997603201211002	2992.809603633	-0.391231588125...	-26.6310976555384	-79.7018048187837	-26.6310976555384	-79.8932929666152	0.0	0.0	0.0	0.0	5.0	37.0

Figure 2-16: Node output model in the database.

- Stp: Simulation instant.
- Node: ID of the corresponding node.
- State: State of the node. 0: Branch f, 1: OFF, 2: Branch r.
- Vpu: Voltage in p.u on the DC side of the node.
- V: Voltage in V on the DC side of the node.
- Vg: Rail voltage on the DC side of the node.
- Conv_I: Current through the node converter.
- Conv_P: Power by the node converter.
- I_Inj: Sum of all the injected currents in the DC side of the node including that the slack current.
- Total_P: Total power injected into the node on the AC side.
- IL_DC: Drained current on the DC side.
- PL_DC: Power drained on the DC side.
- PL_AC: Power drained on the AC side through the TP files.
- P_Bus: Power transferred to buses on the AC side.
- Pos_X: X coordinate of the node.
- Pos_Y: Y coordinate of the node.

Chapter 3

Economic Module Implementation

3.1 Aim

Besides its technical and infrastructural features, performance and environmental impact, the convenience of a given transportation technology must not leave out the correct assessment of its costs; this is by the way a priority when evaluating the efficiency, effectiveness and quality of an existing service, or calculating the needed resources to realize an action on a system, or even when comparing different scenarios of a system's layout.

Railway operators are heavy users of electricity resource with the increasing use of electric trains. Therefore, it is a fundamental target for them to minimize electricity costs; choosing the right electricity tariff and its features optimally is essential for reducing company costs and improving competitiveness. In particular, their aim is to minimize the cost by selecting the optimum contracted power and reducing as much as possible the heavy penalties for excess of power demand over the power contracted in certain time periods (which is usual in a lot of countries).

Consequently, CAF TE has seen the need of continuing developing its simulators not only from a technicho-economical optimal infrastructure sizing point of view, but also from the need of being more competitive in terms of the operation costs. Therefore, the goal perused with that economic module is to allow the company to evaluate in advance to the start of operation the cost of the system due to electric variables, these are power and energy requirements. Actually, not only these cost will compose the bill, however, these are the ones that can be optimized and depend itself of the way of operating the system. There are other terms that appear each month on the bill such as the hiring of measurement equipment or diverse taxes, however, these terms can be easily added as a percentage of the mentioned electric costs. Also, costs such as the investment done and the maintenance of the network are vital to perform a complete economic evaluation, nonetheless, these term are out of the scope of this work and, therefore, they are not considered.

Therefore, in the present section, there are presented the regulations that define that operation cost based only on electric variables and its subsequent implementation and thus does not take into account any additional cost.

3.2 Introduction

During the last few years, many countries have undergone the liberalization of the electricity market [5, 11]. This situation has been a genuine step forward to improve competitiveness by offering new tariffs from electricity companies. Usually, consumers are free to choose the energy provider and tariff according to the norms of the country. However, there is no such thing as complete deregulation of electricity markets. In practice, governments may establish certain restrictions to competition or charges and taxes in the electricity tariff. For example, access charges [14] reflect costs related to the maintenance of the transmission and distribution network infrastructure or costs related to regulated activities.

Generally speaking, the cost-structure usually takes into account many factors related to the type of consumer (domestic, industrial, etc.), quality of service, voltage level, location or season.

However, the vast majority of electrical systems base their tariff structure on three main foundations:

- Charges for capacity or access, based on the amount of electrical power (€/kW) demanded from the grid and expected by the user to be guaranteed.

- Charges for active energy consumed, based on the cost of the price of the energy (€/kWh) demanded by the end user.

- Other charges, such as taxes, environmental commitments, penalties, etc.

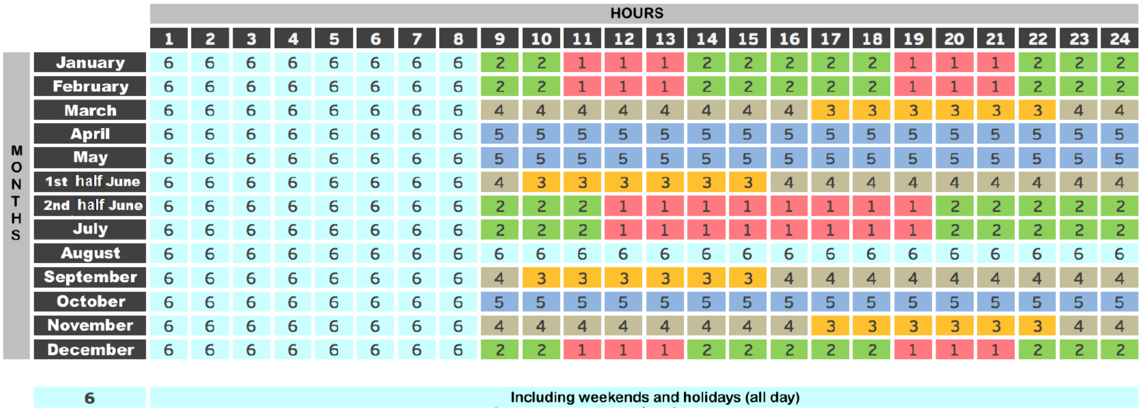
For large customers the charges for capacity or access play an important role since they can be an important component in the bill of large consumers. In addition, these charges are subject to an hourly variability within the day and a daily variability within the season of the year. Time-of-use (TOU) is a term that refers to the application of different charges for energy use in different time periods in a way that reflects generation costs and encourages energy consumption in periods that are less critical to the system. Time differentiation (hourly–seasonal) is practised by most countries.

There are many examples of countries which apply a time or seasonal differentiated component to the tariff. Some examples include England, where tariffs are peak/off-peak and seasonal; France, where there are two seasons and peak/non-peak tariffs; Italy, where, for high voltage rates, the kWh charge varies depending if the period is peak, high, medium or off-peak; Netherlands, where for low voltage customers, the kWh charge may be split in a TOU charge for off-peak and regular hours; Norway, where the energy component is time and point-differentiated (winter day, winter night/weekend and summer); or California, where most rates vary by season and period (super peak/peak/off-peak) [3].

In the case of Spain, it is common to make different charges depending on the time of day, the day of the week, and even the month of the year due to the underlying costs of the system and the need to rationalize the uses of energy by users. In Fig.3-1 it is shown the Spanish tariff structure for customers that have 6-period hourly division (P1, P2, P3, P4, P5, and P6) with different energy and power prices.

Therefore, the price for access capacity as well as the price of energy will change according to the restrictions referred to above, being the price much more expensive for the power and energy demanded in peak periods versus off-peak periods.

This implies that strategies that minimize costs in the most expensive periods



	HOURS																							
MONTHS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	6	6	6	6	6	6	6	6	2	2	1	1	1	2	2	2	2	2	1	1	1	2	2	2
February	6	6	6	6	6	6	6	6	2	2	1	1	1	2	2	2	2	2	1	1	1	2	2	2
March	6	6	6	6	6	6	6	6	4	4	4	4	4	4	4	4	3	3	3	3	3	3	4	4
April	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
May	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
1st half June	6	6	6	6	6	6	6	6	4	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
2nd half June	6	6	6	6	6	6	6	6	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2
July	6	6	6	6	6	6	6	6	2	2	2	1	1	1	1	1	1	1	1	2	2	2	2	2
August	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
September	6	6	6	6	6	6	6	6	4	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
October	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
November	6	6	6	6	6	6	6	6	4	4	4	4	4	4	4	4	3	3	3	3	3	3	4	4
December	6	6	6	6	6	6	6	6	2	2	1	1	1	2	2	2	2	2	1	1	1	2	2	2

6 Including weekends and holidays (all day)

Figure 3-1: Spanish 6.1 tariff structure (six periods for consumers with >1 kV and >450 kW).

must be tackled in favour of those where the system is less loaded, and therefore it is cheaper to consume electricity. The problem is that, in many cases, large consumers cannot change their consumption habits either because their production process does not allow for changes in production schedules or because the provision of services must take place at a certain time as is the case of railway transport.

This does not imply that there are no other mechanisms that allow to face a reduction in costs based on the contracted electricity power in each of the hourly periods that make up the selected tariff. Normally, users contract a certain amount of power with the utilities for each of the periods of use, but this power may not be suitably adjusted, so that it may be excessively high involving large costs, or lower than the value required so that the utility will apply large penalties. In short, an incorrect choice of the contracted capacities, by excess or defect, raises unnecessarily the energy costs of the customer.

In a highly dynamic network as it is the railway network, it is normal that peaks of demanded power occur at certain times. That power peaks may be higher than the maximum power contracted by the railway operator and when this occurs, the electricity supplier company applies an economic penalty.

In low voltage (LV) networks these situations are managed by means of a power control switch (PCS), which causes the power supply cut-off in case of exceeding the established limit. However, in high voltage (HV) networks, a maximeter is used that does not cut-off the supply, but penalties are applied when power exceeds occur.

The maximeter works taking note of the power being demanded and does so in 15-minutes blocks (this average time may depend on the country). For each of these blocks, it calculates the average power required in that specific period of time, which actually is the power which registers as the demanded power for that particular period.

As already mentioned there is a general structure to define the electricity bill, however, each country has particularities to adequate it to its special conditions (i.e. seasonality). CAF TE has required the implementation of the economic module with the Spanish electricity rates. This decision, far from limiting the operability of the module, is expected to be the basis for a future expansion of it, in which other many countries electricity tariffs will be considered.

The Spanish access rates to the electricity transmission and distribution networks are detailed in Royal Decree (RD) 1164/2001, of October 26. There is addressed the method to calculate the different access rates that consists of applying the binomial: power term plus energy term.

Following, it will be explained the procedure to calculate these access rates with their correspondent power penalties due to an excess of demand using the appropriate mathematical formulae and examples according to the mentioned RD. A distinction will be made between 3-period rates (3.0A and 3.1A), and 6-period rates (6.1, 6.2, 6.3, 6.4 and 6.5).

3.3 Spanish access rates definition

The access rates of general application, with no other conditions than those derived from the voltage at which the connection is made and those established for each of them, according to the article 7 of the RD 1164/2001 are as follows:

a) Low voltage tariffs:

They will be applied to supplies made at voltages not exceeding 1 kV and are as follows:

- Rate 2.0A: simple rate for low voltage.
- Rate 3.0A: general rate for low voltage.

b) High voltage tariffs:

They will be applied to supplies made at voltages greater than 1 kV and are as follows:

- Rate 3.1A: three-period specific rate for voltages from 1 to 36 kV.
- Rate 6: general rates for high voltage.

For each of these high voltage rates (the ones which apply in the present project), its application conditions are as follows:

1. Rate 3.1A: three-period rate that will apply to supplies in voltages between 1 and 36 kV with power contracted in all tariff periods equal to or less than 450 kW.
2. Rate 6: six-period rate that will be applied to any voltage supply between 1 and 36 kV with contracted power in any of the rate periods higher than 450 kW and any supply at higher voltages than 36 kV.

   Its modalities, depending on the service voltage, are (see Table 3.1):

Table 3.1: Access rate 6 classification in terms of voltage level.

Voltage level	**Tariff**
$1 \text{ kV} \leq V < 36 \text{ kV}$	6.1
$36 \text{ kV} \leq V < 72.5 \text{ kV}$	6.2
$72.5 \text{ kV} \leq V < 145 \text{ kV}$	6.3
$V \geq 145 \text{ kV}$	6.4
International connections	6.5

For all HV rates the power contracted in the different periods will be such that the power contracted in a period rate (Pn + 1) is always greater than or equal to the power contracted in the previous rate period (Pn). That is, the contracted power in P1 must be less than or equal to that of P2, and so on as indicated in equation (3.1):

$$P_{c(P1)} \leq P_{c(P2)} \leq P_{c(P3)} \leq P_{c(P4)} \leq P_{c(P5)} \leq P_{c(P6)} \tag{3.1}$$

In the official state bulletin (BOE-A-2020-1066), circular 3/2020 of January 15, the last modification of the hourly periods of the transport and distribution tolls of the Spanish system is established.

It is important to comment that the Spanish territory is divided in four: the Iberian Peninsula, Balearic Islands, Canary Islands and Ceuta and Melilla. In consequence, the time differentiation (hourly and seasonal) could slightly vary between them. Nonetheless, in the present work only the general case of the Iberian Peninsula has been considered.

The hourly discrimination of 3-rates differentiates the hours of the year into three time periods (see Table 3.2): period 1 (peak), period 2 (mid-peak) and period 3 (valley or off-peak).

Table 3.2: Definition of the time periods for 3-rates.

Summer & winter		
P1	P2	P3
10 a-m - 2 p.m 6 p-m - 10 p.m	8 a-m - 10 a.m 2 p-m - 6 p.m 10 p-m - 0 a.m	0 a.m - 8 a.m

The time discrimination of six periods differentiates the hours of the year into six time periods (see Table 3.3) depending on the season, the day of the week and the time of day as follows:

a) Definition of electrical seasons: for the purposes of application in transportation and distribution tolls, the year will be considered divided into four seasons, including in each of them the following months:

   (i) High season: January, February, July and December.

   (ii) Upper-middle season: March and November.

(iii) Medium season: June, August and September.

(iv) Low season: April, May and October.

b) Definition of the types of days: for the purposes of applying transportation and distribution tolls, the types of days are classified as follows:

(i) Type A: Monday to Friday, not high season holidays.

(ii) Type B: Monday to Friday, not medium-high season holidays.

(iii) Type B1: from Monday to Friday, not mid season holidays.

(iv) Type C: Monday to Friday, not low season holidays.

(v) Type D: Saturdays, Sundays and holidays.

Table 3.3: Definition of the time periods for 6-rates: times to be applied by type of day in Spain.

Periods	**Day Type**				
	Type A	**Type B**	**Type B1**	**Type C**	**Type D**
P1	9 a.m - 2 p.m 6 a.m - 10 p.m	-	-	-	-
P2	8 a.m - 9 a.m 2 p.m - 6 p.m 10 p.m - 0 a.m	9 a.m - 2 p.m 6 p.m - 10 p.m	-	-	-
P3	-	8 a.m - 9 a.m 2 p.m - 6 p.m 10 p.m - 0 a.m	9 a.m - 2 p.m 6 p.m - 10 p.m	-	-
P4	-	-	8 a-m - 9 a.m 2 p.m - 6 p.m 10 p.m - 0 a.m	9 a-m - 2 p.m 6 p.m - 10 p.m	-
P5	-	-	-	8 a-m - 9 a.m 2 p.m - 6 p.m 10 p.m - 0 a.m	-
P6	0 a.m - 8 a.m	0 a.m - 8 a.m	0 a.m - 8 a.m	0 a.m - 8 a.m	All day long

As it has been previously introduced, there is a quite significant difference in price for both energy and power depending on the tariff period. Tables 3.4, 3.5, 3.6, 3.7 contain a summary of the current prices according to the Spanish Ministerial Order IET/2444/2014 for the contracted electric power and the energy demand of the three and six periods above mentioned. Note the important difference between the most expensive period P1, as opposed to the cheapest period P6. For example, for the access rate 6.1 the power price for P1 is about 39 €/kW almost six times greater than for P6. For energy, the difference is even more evident, reaching more than ten times the price for period P1 compared to period P6.

Table 3.4: 3.x access rates: power term price (€/kW · year).

Toll	**1**	**2**	**3**
3.0	40.728885	24.437330	16.291555
3.1	59.173468	36.490689	8.367731

Table 3.5: 3.x access rates: energy term price (€/kWh).

Toll	**1**	**2**	**3**
3.0	0.018762	0.012575	0.00467
3.1	0.014335	0.012754	0.007805

Table 3.6: 6.x access rates: power term price (€/kW · year).

Toll	**1**	**2**	**3**	**4**	**5**	**6**
6.1	39.139427	19.586654	14.334178	14.334178	14.334178	6.540177
6.2	22.158348	11.088763	8.115134	8.115134	8.115134	3.702649
6.3	18.916198	9.466286	6.927750	6.927750	6.927750	3.160887
6.4	13.706285	5.019707	5.019707	5.019707	5.019707	2.290315
6.5	13.706285	5.019707	5.019707	5.019707	5.019707	2.290315

Table 3.7: 6.x access rates: energy term price (€/kWh).

Toll	**1**	**2**	**3**	**4**	**5**	**6**
6.1	0.026674	0.019921	0.010615	0.005283	0.003411	0.002137
6.2	0.015587	0.011641	0.006204	0.003087	0.001993	0.001247
6.3	0.015048	0.011237	0.005987	0.002979	0.001924	0.001206
6.4	0.008465	0.007022	0.004025	0.002285	0.001475	0.001018
6.5	0.008465	0.007022	0.004025	0.002285	0.001475	0.001018

As aforementioned, a typical electric bill has the following components:

$$\text{Total Charges (TC)} = \text{Capacity Charges (CC)} + \text{Energy Charges (EC)} + \text{Additional Charges (AC)} \qquad (3.2)$$

The Capacity Charge CC component can be expressed as the sum of two terms:

$$CC = CC_{contract} + CC_{excess}, \tag{3.3}$$

where $CC_{contract}$ is the charge that depends on the contracted capacity and CC_{excess} the penalty on demand in excess of the contracted capacity.

The general calculation of the billing term for contracted power and the billing term for consumed energy are presented below.

- Access power billing term: it will be the sum resulting from multiplying the contracted power in each hourly period by the price of the corresponding power term, according to the following equation (3.4):

  $$CC_{contract} = \sum_{p=1}^{p=i} T_{P_p} \cdot P_{C_p}, \tag{3.4}$$

  where T_{Pp} is the price of the power term of the period p, expressed in €/kW and year; P_{Cp} is the contracted power in the period p, expressed in kW; and i is the number of periods of the corresponding access rate.

  The CC_{excess} term calculation is exposed in the two following subsections since it depends on the selected tariff.

- Active energy billing term: it will be the sum resulting from multiplying the energy consumed or, where appropriate, estimated in each hourly period by the price of the corresponding energy term, according to the following equation (3.5):

  $$EC = \sum_{p=1}^{p=i} T_{e_p} \cdot E_p, \tag{3.5}$$

  where T_{e_p} is the price of the energy term of the period p, expressed in €/kWh; E_p is the energy consumed in the period p, expressed in kWh; and i is the number of periods of the corresponding access rate.

In the case of a having billing term for the power demand, its billing will depend on whether the user benefits from a three-period or six-period rate. Correspondingly, in the next subsections both methods of calculation are exposed.

The control of the power demanded will be carried out by means of the control and measurement devices in accordance with the provisions of the regulation of measurement points of the electrical system, approved by RD 1110/2007 of August 24.

3.3.1 Power billing term in access rates of 3-periods

The power term to be billed in the case of three-period rates rather than being two independently terms (contracted and demanded), a total power term is taken into account to compute the bill.

The value of this power is obtained as a function of the maximum power demanded in each period P_{Mdi} and registered in each tariff period (hourly intervals), as indicated by equation (4.3).

$$P_{C_p}* : \begin{cases} \text{if } P_{Mdi} < 0.85 \cdot P_{C_p} \rightarrow P_{C_p}* = 0.85 \cdot P_{C_p} \\ \text{if } 0.85 \cdot P_{C_p} \leq P_{Mdi} \leq 1.05 \cdot P_{C_p} \rightarrow P_{C_p}* = P_{Mdi} \\ \text{if } P_{Mdi} > 1.05 \cdot P_{C_p} \rightarrow P_{C_p}* = P_{Mdi} + 2 \cdot (P_{Mdi} - 1.05 \cdot P_{C_p}) \end{cases} \tag{3.6}$$

Therefore, to compute the total power term bill, the corresponding modified contracted power $P_{C_p}*$ must be substituted in equation (3.4).

3.3.2 power billing term in access rates of 6-periods

Unlike the previous case, for the six-period access tariffs the power term is calculated with the contracted power and the power penalty separately, instead of modifying the power to be billed before applying tolls.

Equation (3.7) shows how to calculate cost of excess power or penalty for any

6-period rate.

$$CC_{excess} = \sum_{p=1}^{p=i} K_i \cdot 1,4064 \cdot A_{ei}, \tag{3.7}$$

where the K factor depends on each tariff period as shown in Table 3.8, the penalization factor A_{ei} depends on equation (3.8) and i is the number of hourly periods of the corresponding toll power billing term.

Table 3.8: K-factor values for the different tariff periods.

Period	1	2	3	4	5	6
K_i	1	0.5	0.37	0.37	0.37	0.17

$$A_{ei} : \begin{cases} \text{if } P_{dj} > P_{C_p} \rightarrow A_{ei} = \sqrt{\sum_{j=1}^{n} (P_{dj} - P_{C_p})^2} \\ \text{if } P_{dj} \leq P_{C_p} \rightarrow A_{ei} = 0 \end{cases} \tag{3.8}$$

where P_{dj} is the power demanded in each of the quarters of hour j of the period p in which the contracted power for that period P_{C_p} has been exceeded, expressed in kW.

3.4 Implementation of the calculation of the electric bill in RailNeos 3.0

As a first approach to develop the economic module, it was independently implemented in *Matlab* taking as input the output file of the simulation from RailNeos. Later and after it was validated, the module was included in the post-processing of the simulator.

3.4.1 Input data

The simulator interface, after having defined and simulated a network, allows the user to download the results. Theses files are collected in a folder named with the same name given to the network in the interface. That folder contains the three databases previously explained (*net.db*, *res.db* and *post.db*) as well as a folder named 'COST' that contains the four csv files that were uploaded to the simulator to define the different access rates.

The reading of the simulation results as input to the economic module will be performed by the function 'DCTS_Input_Data.m'. This module only receives a single input that is the 'case_name', that is the name given to the simulated network. This way the program will access to the required files corresponding to that case.

This first function is used to get the network data and reformat it in such way that later the required operations to compute the cost can be done easily and automatically independently of the individual network characteristics. To do so, three main steps have been done as following is presented.

Configuration of the economic module

The data related with the access rates prices and their time periods definition is defined in the folder 'COST'. This folder contais four csv files: *Timing_1*, *Timing_2*, *Price_P* and *Price_E*.

The files that contain the period number by hour and day type (generally identified by the month of the year) are *Timing_1* and *Timing_2*. These tables follow the structure shown in Table 3.9: the first row contains a header (the different day types of the year), the second row the number of days per month and the following ones the number of period corresponding to each hour of the day (defined in the first column in minutes). The structure for *Timing_2* is the same, but with two extra day types and six different periods since it defines 6-rates.

Therefore, in order to obtain a matrix of only integer numbers to define the periods by hour and da type, the program removes the first two rows and the first column and loads the resulting matrix to $MatrixPeriodsxX$ variable. The second row is saved in a vector in a different variable ($DaysPerMonthxX$).

Similarly, the files *Price_P* and *Price_E* define the regulated prices of power (€/kW $\cdot$ year) and energy (€/kWh) for each of the 3-rate and 6-rate tariffs (see Table 3.10). Therefore, again, the first row and the first column must be removed in

Table 3.9: Csv file *Timing_1* structure definition.

Time	January	February	March	...	December
0	31	28	31	...	31
0	3	3	3	...	3
60	3	3	3	...	3
120	3	3	3	...	3
...	...	...	...	...	...
1380	2	2	2	...	2

order to obtain a matrix of integer numbers to easily operate with. These matrixes are save as (*MatrixPricesTPA* and *MatrixPricesTEA*).

Table 3.10: Csv file *Price_E* structure definition.

Period	**3.0**	**3.1**	**6.1**	**6.2**	**6.3**	**6.4**	**6.5**
1	0.018762	0.014335	0.026674	0.015587	0.015048	0.008465	0.008465
2	0.012575	0.012754	0.019921	0.011641	0.011237	0.007022	0.007022
...	...	...	...	...	...	...	...
6	0	0	0.002137	0.001247	0.001206	0.001018	0.001018

In Fig. 3-2, it is shown the part of the input function that reformat the data as above mentioned.

Economic parameters set to the case of study

To access to the database the SQL module of *Matlab* (sqlite) is used (see Fig. 3-3). In this part of the program, it is read the access rate (named as *mode*) and the contracted power per period (P_{C1} to P_{C6}) in each substation. Obviously, nodes type 0 - disconnected from AC side - are not taken into account.

Instantaneous power consumptions

The last part of the input data reading is the reading of the instantaneous power consumptions in the substations from the AC side. This is a result given by RailNeos as a result of the simulation.

The simulation is performed according to the trains schedule. This implies that

```
% ACCESS RATES: PRICES and TIME DISCRIMINATION

% with function dlmread, access to the file using its global path
% path = {path to workspace}
% folder_name = {name_of_network}
%
% We set the dlmread function to start reading at column 2 and row 3
MatrixPeriods3X = dlmread(strcat(path,folder_name,'/COST/Timing_1.csv'), ',', 2, 1);  % define periods for 3X rates
MatrixPeriods6X = dlmread(strcat(path,folder_name,'/COST/Timing_2.csv'), ',', 2, 1);  % define periods for 6X rates
MatrixPricesTPA = dlmread(strcat(path,folder_name,'/COST/Price_P.csv'), ',', 1, 1);   % price for POWER TERM
MatrixPricesTEA = dlmread(strcat(path,folder_name,'/COST/Price_E.csv'), ',', 1, 1);   % price for ENERGY TERM

% Number of days per month
% In this case dlmread is only set to remove the first row and the first column
Matrix3X = dlmread(strcat(path,folder_name,'/COST/Timing_1.csv'), ',', 1, 1);  % define periods for 3X rates
Matrix6X = dlmread(strcat(path,folder_name,'/COST/Timing_2.csv'), ',', 1, 1);  % define periods for 6X rates
DaysPerMonth3x = Matrix3X(1,1:end-3);  %[31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31] by default;
DaysPerMonth6x = Matrix6X(1,1:end-1);  %[22, 19, 22, 21, 21, 11, 10, 22, 22, 21, 22, 21, 20, 111] by default;
```

Figure 3-2: Matlab function used to get the input data for the implementation of the economic module (part I).

```
% Get access to the database
db_FileName = strcat(path,folder_name,'res.db');
db = sqlite(db_FileName); % open the results database

% Obtain acces rate (mode) and the contracted power per period (p1 to P6) in each substation.
sql = sprintf([...
'SELECT Node.ID, Base.Mode, Base.P1, Base.P2, Base.P3, Base.P4, Base.P5, Base.P6 FROM Base, Node WHERE Base.ID == Node.Base AND Node.Type !=0']);
TmpMat = fetch(db, sql);
Node_ID = double(cell2mat(TmpMat(:,1))); % Nodes ID vector
NodeNum = length(Node_ID);
Mode = double(cell2mat(TmpMat(:,2))); % Access rate definition
Pcontract = cell2mat(TmpMat(:,[3,4,5,6,7,8]))'; % Contracted power definition
```

Figure 3-3: Matlab function used to get the input data for the implementation of the economic module (part II).

it exists a 'starting time' and a 'simulation time'. Therefore, these times should be taken into account since the power and energy prices will depend on the time of the day. The instantaneous power consumptions will be stored in a matrix P where each column correspond to each feeding substation and each row to one timestamp (see Fig. 3-4).

```matlab
%% Get Power Consumptions
%Request the Start Time and the simulation time from Cfg table.
sql = sprintf([...
'SELECT Cfg.Start_Time, Cfg.Sim_Time FROM Cfg']);
TmpMat = cell2mat(fetch(db, sql));
StartTime = TmpMat(1); %in sec % The start time of the calculation
EndTime =  StartTime + TmpMat(2); %in sec % The end time of the calculation

% Create SQL query to read the total power in each feeding substation
P = zeros(EndTime-StartTime, NodeNum); % power vector
for k = 1 : NodeNum  %Loop over feeding substations
        Node = Node_ID(k);  %Get feeding substation ID
        %Request power and time vectors of the selected substation.
        sql = sprintf([...
        'SELECT Stp.t, OUT_Node.Total_P FROM OUT_Node, Stp WHERE Stp.ID = ', ...
        'OUT_Node.Stp AND OUT_Node.Node = %d AND Stp.t <= %f'], Node, EndTime-1);
        TmpMat = cell2mat(fetch(db, sql));
        P(:,k) = TmpMat(:, 2); %only data of the simulated period, NOT 24h by default.
        % Signs convention for Total power (kW): -ve demand (AC to DC), +ve regeneration (DC to AC)
end
t = TmpMat(:, 1); % Time vector (s)
```

Figure 3-4: Matlab function used to get the input data for the implementation of the economic module (part III).

3.4.2 Obtaining the vector of consumed powers

The power consumption in each feeding substation is given for each sample time, that is for each second. However, the measuring devices do not register that instantaneous power, but as above mentioned does it in 15-minutes blocks. Therefore, the measurement devices will send the average power of those 15-minutes periods. From now on, this it will be named as period average power.

As it will be calculated the bill for a day type (note that RailNeos only allows to do simulations of a maximum of a full day), it will be created a power profile of 24 hours in which the power vector will be placed at the corresponding time defined in the simulation. The rest of the power consumptions (out of operating the time) will be set to zero (gap filling). These two steps are shown in Fig. 3-5.

```

%% Select Simulation Sampling Time (Fixed values by the simulator)
SamplePerSecond = 1; % one sample per each second (for all simulation)
SecondPerPeriod = 15 * 60; % number of seconds in 15 minutes
SamplePerPeriod = SamplePerSecond * SecondPerPeriod; % number of samples in a single period = 900
SamplePerHour = SamplePerSecond * 3600; % number of samples in a single hour
PeriodPerHour = SamplePerHour/SamplePerPeriod; %number of period within 1 hour = 4

%% Gap filling of the power matrix
Ptot  = zeros(24*3600, 1); %'Organize P in the 24h vector (86400 instants). Ptot vector initialized to 0.
%Copy vector P in the corresponding time inside the vector Ptot
for Index = StartTime : EndTime
        Ptot(Index) = P(Index - StartTime + 1);
end

%% Vector initialization for average power by each 15-minutes
NodeNum = size(Ptot,2); %number of feeding substations
Period_Count = ceil(length(Ptot) / SamplePerPeriod); % The count of full period in a simulation time
Period_Pavg     = zeros(Period_Count, 1); % The average  power in each 15 minutes

%% Average power calculation
SampleIndex     = 1 : SamplePerPeriod; % The samples range of the first period (1:900)seconds
for k = 1 : Period_Count %number of 15-minutes bocks or periods in a simulation = 96
        Period_Pavg(k) = mean(Ptot(SampleIndex)); %average power calculation of each period
        SampleIndex = SampleIndex + SamplePerPeriod; % Update the sample index to the next period
end
```

Figure 3-5: Matlab function used to reformat the power consumption matrix (Part I).

Although the sensors take 15-minute averages, they will be aggregated. For 3-rates and to compute the energy term it will be used an hourly average and peak values. Thus, in a second stage this aggregation is done as shown in Fig. 3-6.

```matlab
%% Vector initialization for average power by each 60-minutes
Hour_Count = 24; % The count of 1 hour in a simulation time
Hour_Pavg = zeros(24, 1); % The average  power in each hour
Hour_Pmax = zeros(24, 1); % The maximum power in each hour

for k = 1 : Hour_Count %loop over the hour of a single day
        IndexFirstMeasure = (k - 1) * PeriodPerHour + 1; %Index of the first period of current hour
        IndexLastMeasure = IndexFirstMeasure + PeriodPerHour - 1; % Index of the last period of current hour
        Hour_Pavg(k) = mean(Period_Pavg(IndexFirstMeasure:IndexLastMeasure, n)); %hourly average value of registered powers
        Hour_Pmax(k) = max(Period_Pavg(IndexFirstMeasure :IndexLastMeasure, n)); %hourly peak power of registered values
end
```

Figure 3-6: Matlab function used to reformat the power consumption matrix (Part II).

3.4.3 3-rate tolls bill calculation

To compute the annual cost of operation of a network it has been taken into account two terms as above mentioned: the active power and energy terms.

Power term

As previously presented in 3-rate tolls, there is only charged a single power term in such a way that if a power excess occurs instead of charging an additional term, the contracted power is modified according to the regulation presented in section 3.3.1.

To do so, it is required to compare the maximum power registered in each of the three periods (hourly maximum power) with the contracted in each of that periods along the twelve months. Therefore, in a first step, a matrix containing that maximum power registered per time period is built (see Fig. 3-7). Later, this matrix is compared with the contracted power per period and taking advantage of that loop, the modified power ($P_{C_p}*$), that is the one that will be used to compute, the bill is obtained (see Fig. 3-8).

```
%% Build a matrix (3x12) to register the maximum power registered in
     each of the periods. That is the maximum value of the hourly
    average power (Hour_Pmax).
MaxPowerPerPeriodPerMonth = zeros(length(Periods), size(
    MatrixPeriods3X ,2) - 3);
for month=1:12
          for k = Periods
                    PeriodIndex = ismember(MatrixPeriods3X(:, month), k)
                        ;
                    if (sum(PeriodIndex) >= 1) %(24x12)
                              MaxPowerPerPeriodPerMonth(k, month) = max(
                                  Hour_Pmax(PeriodIndex));
                    end
          end
end
```

Figure 3-7: Matlab snippet used to calculate the power term cost for 3-rates (Part I).

Finally, the annual cost of the power term is computed by multiplying the daily power price per period by the number of days of each month and the modified power for each period as shown in Fig. 3-9.

Energy term

To compute the active energy term is needed to calculate previously the energy consumed in each period in each month (see Fig. 3-10). This was done using the hourly average power matrix since the summation of hourly average power in kW is equal to the consumed energy in kWh. The active energy term per month is computed taking into account the days per month and, finally, the annual cost is obtained.

```matlab
%% Check if the maximum measures exceed the contracted power values, if so register the MODIFIED CONTRACTED POWER according to the regulation (3 options) to calculate the bill.
MaxPowerPerPeriodPerMonthModified = MaxPowerPerPeriodPerMonth; % Initialization of the MODIFIED CONTRACTED POWER matrix
for n = 1 : size(MaxPowerPerPeriodPerMonthModified, 2) %loop over all the month
        for r = 1 : size(MaxPowerPerPeriodPerMonthModified, 1) %loop over all the periods
                %If the Consumed Power is less than the 85% of the contrated power, that is the power considered to compute the bill
                if (MaxPowerPerPeriodPerMonthModified(r,n) < LowParameter3x * Pcontract(r))
                        MaxPowerPerPeriodPerMonthModified(r,n) = LowParameter3x * Pcontract(r);
                %If the Consumed Power is between the 85% and 105% of the contrated power, the power considered to compute the bill is the contrated power
                elseif (((LowParameter3x * Pcontract(r)) <= MaxPowerPerPeriodPerMonthModified(r,n)) && MaxPowerPerPeriodPerMonthModified(r,n) <= (HighParameter3x * Pcontract(r)))
                        MaxPowerPerPeriodPerMonthModified(r,n) = Pcontract(r);
                %If the Consumed Power is higher than the 105% of the contrated power, a penalization is applied: Pdi = PMdi + 2 * (PMdi - 1.05*PMi)
                elseif (MaxPowerPerPeriodPerMonthModified(r,n) > HighParameter3x * Pcontract(r))
                        MaxPowerPerPeriodPerMonthModified(r,n) = MaxPowerPerPeriodPerMonthModified(r,n) + 2 * ( MaxPowerPerPeriodPerMonthModified(r,n) - HighParameter3x * Pcontract(r));
                end
        end
end
```

Figure 3-8: Matlab snippet used to calculate the power term cost for 3-rates (Part II).

```
%% POWER TERM BILL CALCULATION FOR 3-RATE TOLLS
PricekWPerPeriodPerDay = MatrixPricesTPA(:,Mode)/sum(DaysPerMonth3x); % price per day [eur/kW*day]
PowerBillPerPeriodPerMonth = zeros(size(MaxPowerPerPeriodPerMonthModified ,1)+1, size(MaxPowerPerPeriodPerMonthModified ,2)); %Bill per period per month matrix  initialization
for n = 1 : size(MaxPowerPerPeriodPerMonthModified , 2) %loop over the months
        for r = 1 : size(MaxPowerPerPeriodPerMonthModified , 1) %loop over the periods
                PowerBillPerPeriodPerMonth(r,n) = MaxPowerPerPeriodPerMonthModified(r,n) * DaysPerMonth3x(n) * PricekWPerPeriodPerDay(r);
        end
end
PowerBillPerPeriodPerMonth(length(Periods)+1,:) = sum(PowerBillPerPeriodPerMonth); %anual cost of the power term per period per month
PowerBillPerPeriodPerYear = sum(PowerBillPerPeriodPerMonth(length(Periods)+1,:)); %anual cost of the power term
```

Figure 3-9: Matlab snippet used to calculate the power term cost for 3-rates (Part III).

```
AvgEnergyPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods3X , 2)-3); %Average energy matrix initialization
PricekWhPerPeriodPerDay = MatrixPricesTEA(:, Mode); % price per day
EnergyBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods3X , 2) - 3); %Energy bill matrix initialization
%% Compute the energy bill
for month = 1 : size(AvgEnergyPerPeriodPerMonth , 2) %loop over the months
        for k = Periods %loop over the periods
                %Find the periods that present in that actual month
                [row]=find(ismember(MatrixPeriods3X(:, month), k));
                for idx = row'
                        AvgEnergyPerPeriodPerMonth(k, month) = Hour_Pavg(idx) + AvgEnergyPerPeriodPerMonth(k, month);
                end
                EnergyBillPerPeriodPerMonth(k, month) = AvgEnergyPerPeriodPerMonth(k, month) * DaysPerMonth3x(month) * PricekWhPerPeriodPerDay(k); %anual cost per period & month
        end
end
EnergyBillPerPeriodPerMonth(end,:)=sum(EnergyBillPerPeriodPerMonth);
```

Figure 3-10: Matlab snippet used to calculate the active energy cost.

3.4.4 6-rate tolls bill calculation

Again, to compute the annual cost of operation of a network it has been taken into account two terms as above mentioned: the active power and energy terms.

Power term

In 6-rates as exposed in section 3.3.2 the power term is compound by two independently terms: the contracted power term and the power penalization term, if applies.

In Fig. 3-11 it is shown the code used to calculate the contracted power annual cost. It is obtained with the product of daily price of the power per period, the contracted power per period and the total number of days per each month in one year. Finally, the summation of all months is obtained (annual cost).

```matlab
%% FIX POWER TERM DEPENDING ON THE CONTRACTED POWER - COST COMPUTATION
PricekWPerPeriodPerDay = MatrixPricesTPA(:,Mode)/365; %daily price per period
ContractedPowerBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X,2)-1); %Matrix initialization to save the contracted power cost per day type & per perid (7:14). Last row is to compute the aggregation cost of each day type.
for month = 1 : size(MatrixPeriods6X,2) - 1  %Loop over the months or day types (1:14)
      for k = Periods %Loop over the periods (1:6)
            ContractedPowerBillPerPeriodPerMonth(k, month) = Pcontract(k) * DaysPerMonth6x(month) * PricekWPerPeriodPerDay(k); %multiply the dayly price per number of days of that day type in each period
      end
end
ContractedPowerBillPerPeriodPerMonth(end,:) = sum(ContractedPowerBillPerPeriodPerMonth); %matrix of annual cost per day type & period
ContractedPowerBill = sum(ContractedPowerBillPerPeriodPerMonth(end,:)); %total annual cost
```

Figure 3-11: Matlab snippet used to calculate the contracted power cost.

Note that the Spanish regulation gives the power price by €/kW · year, that is the contracted power is paid annually. It does not matter that P1, for example, only appear in five out of the fourteen day types. The total cost will be divided in the different bills over the year independently of the period that appears in that day type or month.

This is of greater importance than it may seem because in the specific case of Spain certain limitations must also be taken into account due to national regulations. There are restrictions to change the contracted electric power within the current year, so that a consumer may not be allowed to change this power or tariff more than once a year and if so, penalizations can be applied.

For the power penalization term calculation it is needed to compare the average power in 15-minutes blocks with the contracted power for each of those periods. If the demanded power is greater than the contracted one, the penalization component is applied according to the exposed in Section 3.3.2. This part was implemented following three steps:

1. A matrix with the power contracted per period and per month is generated. Each column corresponds to one month and each row to one period. Therefore, since each month only have some of the periods (for example, January only have P1, P2 and P6), the not used periods will be filled with a zero (see Fig. 3-12).

```matlab
%% Contracted Power Matrix Generation
ContractedPowerPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods6X,2)-1); %Matrix initialization (6x14)
for month = 1 : size(MatrixPeriods6X,2) %Loop over each moth (1:14)
    for k = Periods %Loop each period (1:6)
        if (sum(ismember(MatrixPeriods6X(:, month), k)) > 0) %Detect if the period appears in each month (24x14)
            ContractedPowerPerPeriodPerMonth(k, month) = Pcontract(k); %matrix generation
        end
    end
end
```

Figure 3-12: Matlab snippet used to calculate the penalization power cost (Part I).

2. To compute the power penalization is required to compare the demanded power in 15-minutes blocks with the contracted power in that period. Therefore, a matrix containing the contracted power in 15-minutes blocks is needed. To

do so, it is used the matrix created in the previous step and input matrix that relates the periods with the hours of the day (*MatrixPeriods6X*). Once that matrix is generated, both the demanded power vector and the contracted power matrix can be compared column by column (month by month) in order to detect if the power demand exceeds the contracted one and, therefore, a penalization must be applied. In these cases the square differences are added to the corresponding period and month in a matrix (A_{ei}). Finally, the square root of this matrix is calculated obtaining the factor defined in (3.8) for each month and period. These two calculation were implemented within the same loop (see Fig. 3-13).

```
%% Penalization factor (Aei) calculation
PowerPerPeriod = zeros(length(Period_Pavg), size(MatrixPeriods6X, 2)-1); %Matrix per period (15min) per month generation initialization (96x14)
Aei = zeros(length(Periods), size(MatrixPeriods6X, 2)-1); % Penalization factor Aei initialization (6x14)
for month = 1 : size(MatrixPeriods6X,2) - 1  %Loop over each month (1:14)
        for k = 1 : length(Period_Pavg) %Loop over each period (1:96)
                h = ceil(k/4); %Get integer numbers of hour for period k
                period_idx = MatrixPeriods6X(h, month); %actual period index
                PowerPerPeriod(k, month) = ContractedPowerPerPeriodPerMonth(period_idx, month); %Matrix per period (15min) per month generation
                if(Period_Pavg(k) > PowerPerPeriod(k, month))
                        Aei(period_idx, month) = Aei(period_idx, month) + DaysPerMonth6x(month) * (Period_Pavg(k) - PowerPerPeriod(k, month))^2;  %Penalization factor calculation
                end
        end
        Aei(:,month) = sqrt(Aei(:,month));
end
```

Figure 3-13: Matlab snippet used to calculate the penalization power cost (Part II).

3. In a last step the penalization cost is computed by multiplying the penalization term (A_{ei}) by a corresponding penalization K factor (see Table 3.8) and a

constant factor ($XFactor$) of 1.4064. This was implement using the code shown in Fig. 3-14.

```
%% Power penalization Bill
FEP = zeros(length(Periods), size(MatrixPeriods6X, 2)-1); % Penalization power bill matrix per period per month initialization (6x14)
PenalizationPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X, 2)-1); %Penalization power matrix per period per month initialization
for month = 1 : size(MatrixPeriods6X,2) - 1 %loop over the months (1:14)
    for k = Periods %loop over the periods (1:6)
        FEP(k, month) = K6x(k) * XFactor6x * Aei(k, month); %Penalization power bill calculation
        PenalizationPerPeriodPerMonth(k, month) = PenalizationPerPeriodPerMonth(k, month) + FEP(k, month); %Penalization power bill saving and one last row to do the aggregation per month(7x14)
    end
end
PenalizationPerPeriodPerMonth(end,:) = sum(PenalizationPerPeriodPerMonth); %Total cost of power penalization per month
PowerPenalizationBill = sum(PenalizationPerPeriodPerMonth(end,:)); % Total cost of power penalization per year

%% POWER TERM BILL
PowerBill = ContractedPowerBill + PowerPenalizationBill; %Total cost of the power terms
```

Figure 3-14: Matlab snippet used to calculate the penalization power cost (Part III).

Energy term

To compute the active energy term is needed to calculate previously the energy consumed in each period in each month (see Fig. 3-15). This was done using the hourly average power matrix since the summation of hourly average power in kW is equal to the consumed energy in kWh. The active energy term per month is computed taking into account the days per month and, finally, the annual cost is obtained.

```matlab
AvgEnergyPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods6X, 2) - 1); %Energy matrix initialization (6x14)
PricekWhPerPeriodPerDay = MatrixPricesTEA(:, Mode); % price per day [eur/kWh]
EnergyBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X, 2) - 1); %Energy matrix cost initialization (7x14)
for month = 1 : size(MatrixPeriods6X, 2) - 1 %1:14
        for k = Periods %1:6
                [row] = find(ismember(MatrixPeriods6X(:, month), k)); %Find the hour (rows) where there is the k period in the actual month
                %Summation of all the hourly average powers = kWh/day
                for idx = row'
                        AvgEnergyPerPeriodPerMonth(k, month) = Hour_Pavg(idx) + AvgEnergyPerPeriodPerMonth(k, month);
                end
                %Calculate the total eur per period per month
                EnergyBillPerPeriodPerMonth(k, month) = AvgEnergyPerPeriodPerMonth(k, month) * DaysPerMonth6x(month) * PricekWhPerPeriodPerDay(k);
        end
end
EnergyBillPerPeriodPerMonth(end,:) = sum(EnergyBillPerPeriodPerMonth); %store in the last row the cost per month
EnergyBill = sum(EnergyBillPerPeriodPerMonth(end,:)); %compute the anual active energy cost
```

Figure 3-15: Matlab snippet used to calculate the active energy cost.

3.4.5 Getting results

As a last step, all the previous functions are organised and automatically called as many times as feeding substations are in order to compute de total annual cost. To do so, the *Matlab* function 'Results.m' has been used.

In a first stage, the functions in charge of getting the input data and calculating the average and maximum power vectors are called as well as the variables that later are required as output are initialized as shown in Fig. 3-16. In this case, it is desired to obtain the total annual cost, but also the different parts that compose it (term due to the access power, term due to penalties and energy term) separately as well as the bill per period in order to later be able to do a post-processing and make various comparisons under different scenarios (different infrastructure configurations or different economic parameters configuration) for the same case of study in order to get the optimal solution.

```matlab
function [ContractedPowerBill,Penalization,EnergyBill,TotalBill,BillPerPeriod6x,BillPerPeriod3x,Period_Pavg]=Results(case_name)
        % Call Input Data Function
        [Ptot, MatrixPeriods3X, MatrixPeriods6X, MatrixPricesTPA,...
        MatrixPricesTEA, Node_ID, Mode, Pcontract, DaysPerMonth3x, DaysPerMonth6x] = DCTS_Input_Data(case_name);
        % Call the function which calculates the max and avg power
        [Period_Pavg, Hour_Pavg, Hour_Pmax] = DCTS_PT(Ptot);
        %Initialize variables that you later want as output
        BillPerPeriod3x = zeros(4,12,length(Node_ID));
        BillPerPeriod6x = zeros(7,14,length(Node_ID));
        ContractedPowerBill = zeros(1,length(Node_ID));
        Penalization = zeros(1,length(Node_ID));
        EnergyBill = zeros(1,length(Node_ID));
        TotalBill = [];

        %% CALL 3 or 6-rate FUNCTION TO COMPUTE THE COST
        %           [...]

end
```

Figure 3-16: Matlab function used to get the cost results (Part I).

In a second stage, a loop over all the feeding substations will be done in order to compute the cost of the whole system. Therefore, substation by substation the program will get the configured economic variables (mode and contracted power per period) as well as its required power averages to be able to call the corresponding function depending on the mode (3-rate or 6-rate) to compute the bill. The results will be saved in a three dimension matrix as shown in Fig. 3-17. That is that will follow the same format up to now in the x- and y-axis (rows: periods, columns: months) and the z-axis will be the different feeding substations in order.

Finally, to obtain the results of each of the study networks, it will only be necessary to enter a simple command with the name of the case of study as input as shown in Fig. 3-18. The proposed methodology of dividing the code in *Matlab* functions and computing the whole system cost instead of entering the substations ID one by one or any other variation thereof is done in order to have a totally automatized code,

```matlab
for node = 1 : length(Node_ID) %loop over all the nodes
        % take mode, average power, maximum power and contracted power per period of the actual node
        ModePerNode = Mode(node);
        Period_Pavg_PerNode = Period_Pavg(:,node);
        Hour_Pavg_PerNode = Hour_Pavg(:,node);
        Hour_Pmax_PerNode = Hour_Pmax(:,node);
        PcontractPerNode = Pcontract(:,node);
        %Call 3-rate function calculation if mode is 1 or 2
        if (ModePerNode <= 2)
                [TotalBillPerPeriod, BillPerYear] = DCTS_Bill_3x(Period_Pavg_PerNode, Hour_Pavg_PerNode, Hour_Pmax_PerNode,MatrixPeriods3X, MatrixPricesTPA, MatrixPricesTEA, ModePerNode, PcontractPerNode, DaysPerMonth3x);
                BillPerPeriod3x(:,:,node)  = TotalBillPerPeriod; % save total    bill in a matrix month by month
        %Call 6-rate function calculation if mode is greater than 2
        elseif (ModePerNode > 2)
                [ContractedPowerBillPerPeriodPerMonth, PenalizationPerPeriodPerMonth, EnergyBillPerPeriodPerMonth,TotalBillPerPeriod, BillPerYear] = DCTS_Bill_6x(Period_Pavg_PerNode, Hour_Pavg_PerNode, MatrixPeriods6X, MatrixPricesTPA, MatrixPricesTEA, ModePerNode, PcontractPerNode, DaysPerMonth6x);
                ContractedPowerBill(node) = sum(ContractedPowerBillPerPeriodPerMonth(end,:));
                Penalization(node) = sum(PenalizationPerPeriodPerMonth(end,:));
                EnergyBill(node) = sum(EnergyBillPerPeriodPerMonth(end,:));
                BillPerPeriod6x(:,:,node) = TotalBillPerPeriod; % save total bill in a matrix month by month
        end
        TotalBill = [TotalBill , BillPerYear];
end
```

Figure 3-17: Matlab function used to get the cost results (Part II).

in which human error is totally minimized when entering the input data of different networks.

```matlab
[ContractedPowerBill,Penalization,EnergyBill,TotalBill, BillPerPeriod6x,BillPerPeriod3x,Period_Pavg]=Results('case_name')
```

Figure 3-18: Matlab command to read cost results.

3.4.6 Economic module validation

The last stage of the economic module implementation was the validation of the same.

Generally, this type of validations are done with a normalized power profiles, however, this module is highly dependent on each country regulations and, therefore, there was not an standard profile available with its economic data. Because of this, it was configured a data base with a simple power profile (see Fig.3-19), which was repeated over the periods (15-min blocks) during three hours.

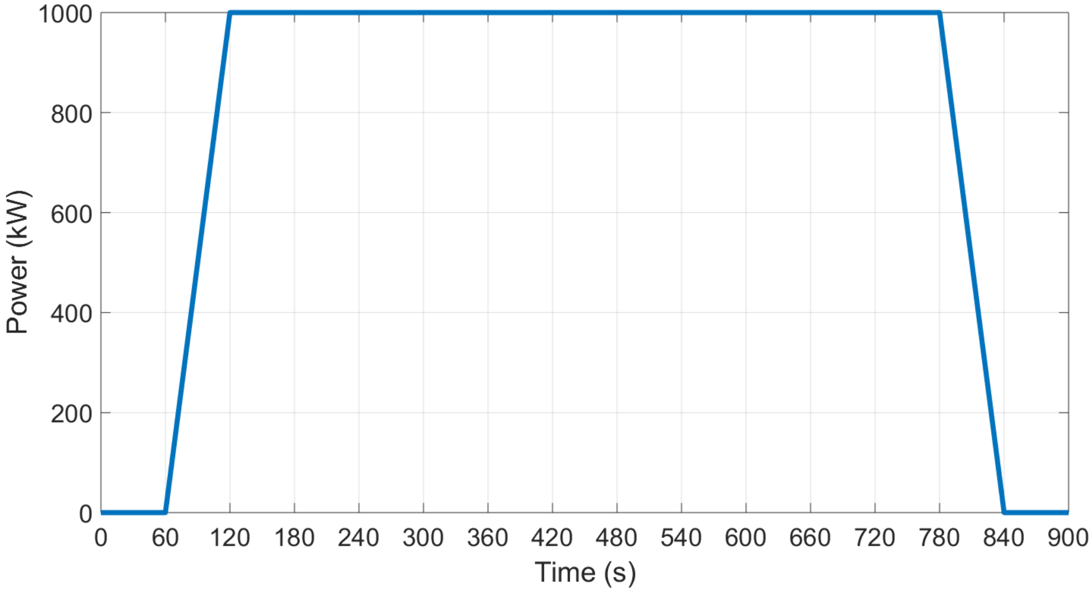


Figure 3-19: Power profile used to performed the economic module validation.

The reason of using that simple profile is that its average power per period and per hour could be easily calculated and, therefore, the output of the economic module can be easily checked by simple operations. To do so, first, is computed the total energy demand in a period by calculating the total area of the profile (3.9) and, later, it can be get the average power of that period by dividing by the duration of that period (3.10).

$$\begin{aligned} \text{Energy} &= \text{triangle 1} + \text{rectangle} + \text{triangle 2} = \\ \frac{1000 \cdot 60}{2} + 1000 \cdot (780 - 120) + \frac{1000 \cdot (840 - 780)}{2} &= 720000 \text{ kJ} \end{aligned} \tag{3.9}$$

$$Power_{avg} = \frac{\text{energy}}{\text{time}} = \frac{720000}{900} = 800 \text{ kW} \tag{3.10}$$

A simulation of three hours (from 7:15 a.m to 10:15 a.m) repeating this power profile has been performed. The configured network has two nodes with that same demand profile. The first one has a contracted power of 1000 kW in all of the periods whereas the second one has it of 500 kW. That configuration is done to check the cost calculation with and without the presence of power penalizations.

Previously to compute the cost, it is required to calculate the average power per period and per hour and the maximum power per hour. That step will also allow to validate that the power vector is organized correctly (depending on the starting and simulating time) as well as the gap filing is also performed correctly.

The average power per period will have 96 rows (24 hours per 4 quarter of an hour each). In this case, the simulation starts just at the beginning of one of these blocks, and, therefore, since the power profile is repeated in each of those periods all the periods involved in the simulation will be equal (800 kW). That power vector is shown in Table. 3.11. This power vector is the same for both nodes.

However, that configuration does not match with hourly intervals and, therefore, the hourly average power (vector of 24 rows) will not be the same in all of the hour divisions. Conversely, the maximum power per hour will be the same in all the hourly periods as in the case of the average power per period as shown in Table. 3.12. These vectors are the same for both nodes.

Table 3.11: Average power per period (15min-blocks) for the validation case.

Time	P_{avg} **(kW)**
0:00	0
0:15	0
0:30	0
0:45	0
1:00	0
...	...
7:15	800
7:30	800
...	...
10:15	800
10:30	0
...	...
23:45	0

Table 3.12: Hourly average power for the validation case.

Time	P_{avg} **(kW)**	P_{max} **(kW)**
0:00	0	0
1:00	0	0
2:00	0	0
...	...	...
7:00	600	800
8:00	800	800
9:00	800	800
10:00	200	800
...	...	...
23:00	0	0

3-rate bill calculation validation

First, the presented network has been configured to check the correct performance of the code for 3 access rates. In particular, it has been check for 3.1 A rate.

Since the average power demand per period (800 kW) is lower than the contracted power per period (1000 kW) during the simulation time, it is clear that the first node will have a null power penalization term. Therefore, to compute the cost, it is only required to calculate the access power term and the energy term.

In order to compute the power term for 3-rates, it is necessary to check equation

(4.3) and see in which of the options fits that case. For the first node, the demand power is lower than the 85% of the contracted power in all the periods. Therefore, the power used to compute the bill is the 85% of the contracted power, that is 850 kW. The results for each period are shown in Table 3.13.

Table 3.13: Power term cost for the node 1 of the validation case with a 3.1 A access rate configuration.

Period	**Power (kW)**	**Power price (€/kW year)**	**Power cost (€/year)**
1	850	59.1735	50,297.45
2	850	36.4907	31,017.09
3	850	8.3677	7,112.57
		€/year	**88,427.11**

To calculate the total energy demand it is necessary to know which are the periods occupied during the simulation time. These billing periods are coincidentally the same the twelve months of the year in 3-rates. In a such way that in a single day it will be 0.75 hours of P3 (from 7:15 to 8:00 a.m) and 2.25 hours of P2 (from 8:00 to 10:15 a.m). Therefore, the energy demanded by day in each period can be easily calculated (3.11):

$$\begin{aligned} E_{P2} &= 2.25 \cdot 800 = 1800\ kWh/day \\ E_{P3} &= 0.75 \cdot 800 = 600\ kWh/day \end{aligned} \tag{3.11}$$

Table 3.14: Power term cost for the node 1 of the validation case with a 3.1 A access rate configuration.

Period	**Energy (kWh)**	**Energy price (€/kWh)**	**Daily energy cost (€/day)**	**Annual energy cost (€/year)**
1	0	0.014335	0	0
2	1800	0.012754	22.9572	8,379.38
3	600	0.007805	4.6830	1,709.30
			€/year	**10,088.68**

Finally, to compute the annual operation cost of the node 1 it is only required to add the power and energy cost of the three periods and the resultant bill is of 98,515.79 €.

Again, to compute the power term cost for node 2, it is necessary to check equation (4.3) and see in which of the options fits that case. Now, the demanded power (800 kW) is higher than the 105% of the contracted power (500 kW) and, therefore, the last option in which a penality is applied must be applied for the case of periods 2 and 3. In the case of period 1, where there is no demand, the first option must be applied again (the power to be paid is the 85% of the contracted power). In equation (3.12) are calculated the resultant modified contracted powers for each period.

$$\begin{aligned} P_{P1} &= 0.85 \cdot 500 = 425 \text{ kW} \\ P_{P2,P3} &= 800 + 2 \cdot (800 - 1.05 \cdot 500) = 1350 \text{ kW} \end{aligned} \tag{3.12}$$

Table 3.15: Power term cost for the node 2 of the validation case with a 3.1 A access rate configuration.

Period	**Power (kW)**	**Power price (€/kW year)**	**Power cost (€/year)**
1	425	59.1735	25,148.74
2	1350	36.4907	49,262.44
3	1350	8.3677	11,296.40
		€/year	**85,707.58**

The energy cost is the same one as in the previous node (see Table. 3.14).

Therefore, the annual operation cost for node 2 is 95,796.3 €.

In Fig. 3.4.6 it can be graphically seen the annual cost results for both nodes. Note the importance of selecting a correct contracted power. In this case, even thought the second node has larger penalizations for periods 2 and 3, the annual bill is a bit lower.

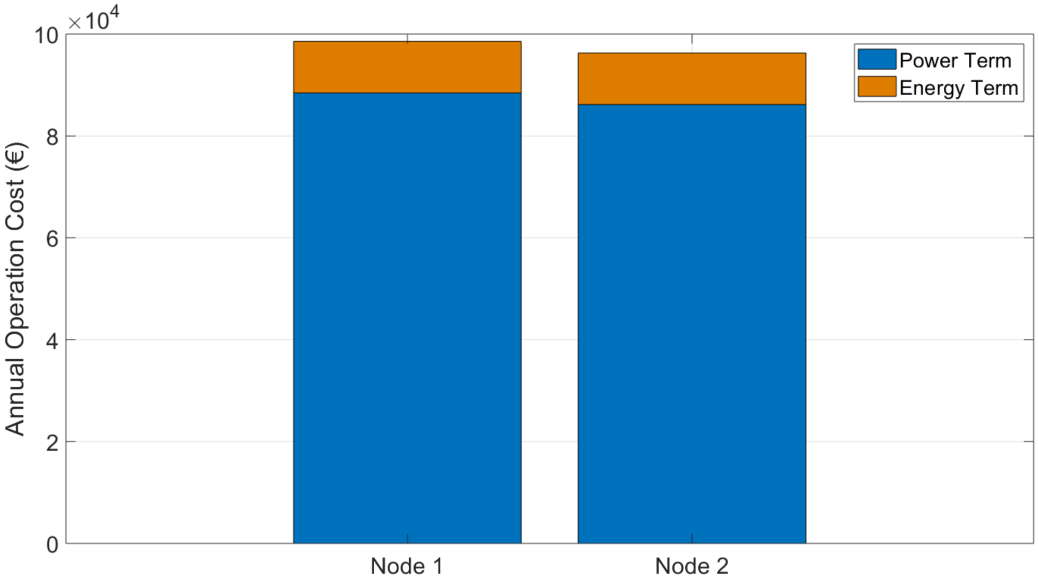


Figure 3-20: Annual bill of the validation case with a 3.1 access rate configuration.

6-rate bill calculation validation

Secondly, it has been checked the correct performance of the code for 6-rates. In particular, it has been set a 6.5 access rate.

As in the previous case, the first node will only have access power term and energy term and the second node will have an additional power penalization term. However, in this case, the power term is independently separated between the access power term and the penalization term.

Following the same criteria as before, the calculation of the annual access power term for node 1 can be checked in Table 3.16.

In this case, all day types do not have the same period distribution for the simulated hours. Therefore, the energy consumption by period should be calculated individually for each month. For the present case, the results are shown in Table. 3.17.

Once that the daily energy demand is obtained, the annual cost of the energy term can be computed by multiplying it by the price of energy per period and the number of days per day type as shown in Table. 3.18.

Table 3.16: Power term cost for the node 1 of the validation case with a 6.5 access rate configuration.

Period	**Power (kW)**	**Power price (€/kW year)**	**Power cost (€/year)**
1	1000	13.706285	13,706.29
2	1000	6.859077	6,859.08
3	1000	5.019707	5,019.71
4	1000	5.019707	5,019.71
5	1000	5.019707	5,019.71
6	1000	2.290315	2,290.32
		€/year	**37,914.86**

Table 3.17: Daily energy demand (kWh) per period & day type for nodes 1 and 2 of the validation case with a 6.5 access rate configuration.

Period	**Jan**	**Feb**	**Mar**	**April**	**May**	**...**	**Dec**	**Holiday**
1	200	200	0	0	0	..	200	0
2	1600	1600	0	0	0	..	1600	0
3	0	0	0	0	0	..	0	0
4	0	0	1800	0	0	..	0	0
5	0	0	0	1800	1800	..	0	0
6	600	600	600	600	600	..	600	2400

Table 3.18: Energy cost (€) per period & day type for nodes 1 and 2 of the validation case with a 6.5 access rate configuration.

Period	**Jan**	**Feb**	**Mar**	**April**	**May**	**...**	**Dec**	**Holiday**
1	1.693	1.693	0	0	0	..	1.693	0
2	11.235	11.235	0	0	0	..	11.235	0
3	0	0	0	0	0	..	0	0
4	0	0	4.113	0	0	..	0	0
5	0	0	0	2.655	2.655	..	0	0
6	0.611	0.611	0.611	0.611	0.611	..	0.611	2.443
€/day	13.539	13.539	4.724	3.266	3.266	..	13.539	2.443
days/month	22	19	22	21	21	..	20	111
€/month	297.858	257.241	103.928	68.586	68.586	..	270.78	271.173
							€/year	**2,193.81**

The total bill for node 1 is 40,108.67 €.

In the case of the node 2 the access power term will be half of node 1 since the contracted power is the half as shown in Table. 3.19. The energy cost will be the same one that for node 1 (see Table 3.17).

Table 3.19: Power term cost for the node 2 of the validation case with a 6.5 access rate configuration.

Period	**Power (kW)**	**Power price (€/kW year)**	**Power cost (€/year)**
1	500	13.706285	6,853.15
2	500	6.859077	3,429.54
3	500	5.019707	2,509.86
4	500	5.019707	2,509.86
5	500	5.019707	2,509.86
6	500	2.290315	1,145.16
		€/year	**18,957.43**

Moreover, for node 2 the equations presented in section 3.3.2 must be applied in order to compute the penalization since the contracted power is quite much lower than the average demanded power per period.

Since the average power per period is the same during all the simulated periods (see Table. 3.11). During these periods will be an excess of power of 300 kW. Hence, to calculate inner summation of the penalization term (A_{ei}), it is necessary to know how many periods (15min-blocks) belong to each period (P1 to P6). The n times that appear a period in a day is shown in Table 3.20.

Table 3.20: Number of times n that a 15min-block appears in each period & month per day.

Period	**Jan**	**Feb**	**Mar**	**April**	**May**	**...**	**Dec**	**Holiday**
1	1	1	0	0	0	...	1	0
2	8	8	0	0	0	...	8	0
3	0	0	0	0	0	...	0	0
4	0	0	9	0	0	...	0	0
5	0	0	0	9	9	...	0	0
6	3	3	3	3	3	...	3	12

Then, using the n values in equation (3.13) it can be obtained the penalization factor by period and month (see Table 3.21) solving equation (3.13).

$$A_{ei_p} = \sqrt{days/month \cdot n \cdot 300^2} \tag{3.13}$$

Table 3.21: Penalization term A_{ei}.

Period	**Jan**	**Feb**	**Mar**	**April**	**May**	**...**	**Dec**	**Holiday**
1	1407.12	1307.67	0	0	0	...	1341.64	0
2	3979.95	3698.64	0	0	0	...	3794.73	0
3	0	0	0	0	0	...	0	0
4	0	0	4221.37	0	0	...	0	0
5	0	0	0	4124.32	4124.32	...	0	0
6	2437.21	2264.95	2437.21	2381.18	2381.18	...	2323.79	10948.97

Finally, from Table 3.21 it is possible to obtain the yearly penalization factor by period adding the values by rows. These values are represented in Table 3.22. Using these values it can be applied the constant $XFactor$ of 1.4064 and K_p (see Table 3.8) in order to obtain the penalization cost by periods.

Table 3.22: Penalization cost calculation.

Period	A_{ei_p}	**XFactor** $\cdot K_p$	**Penalization (€)**
1	4056.43	1.406400	5704.97
2	18540.75	0.703200	13037.85
3	5298.94	0.520368	2757.40
4	13085.21	0.520368	6809.12
5	12470.01	0.520368	6488.99
6	43052.22	0.239088	10293.27
		€/year	**45,091.62**

The total bill for node 2 is 66,239.86 €.

In Fig. 3.4.6 it can be graphically seen the annual cost results for both nodes. In this second case, conversely to the 3-rate case, it can clearly be seen that does not compensate to lower that much the contracted power because the power penalization increase much more the bill than the saving obtained from that strategy.

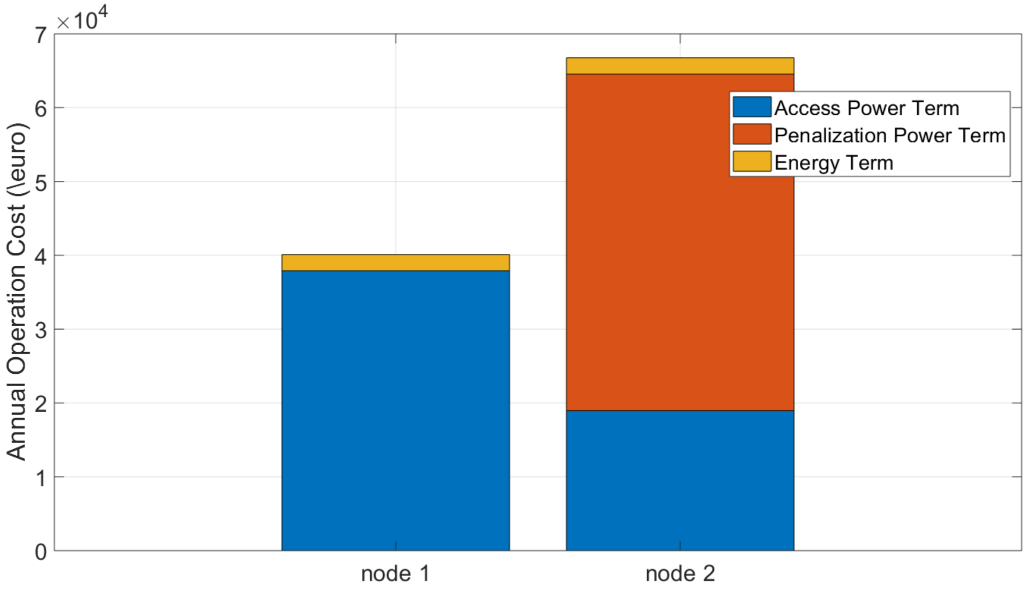


Figure 3-21: Annual bill of the validation case with a 6.5 access rate configuration.

Chapter 4

Contracted Power Optimization for Railway Systems

4.1 Aim

The aim of this work is to minimize the operation cost (only taking into account electric variables) and, consequently, to improve the railway operator competitiveness. To achieve that it is crucial to select appropriately the contracted capacity in each time period. As is was mentioned previously, the Spanish regulation is meant to be applied for a full year and, therefore, the contracted capacities cannot usually be changed within a year. This makes it even more important to make the right decision from the beginning and not to maintain a higher bill than the necessary one during a long period of time, especially if the aforementioned difference in the prices among the periods is considered.

Generally, this kind of methodologies are based on the historical information of the customer. However, in this particular case, the optimization can be done previous to the starting of the activity since it is possible to take advantage of the railway simulation tools. In this particular case of ITINER and RailNeos (see section 2). They will allow operator to predict quite accurately the energy demand of the system. To have that knowledge previously to the start of operation will grant the railway operator to be since the beginning really close the optimal solution avoiding years of unnecessary economic losses.

It is also a interest of the present work to perform a comparison of the effect that the different technologies regarding to the feeding infrastructure and the rolling stock (conventional non-reversible substations, non-reversible substations with off-board energy storage and non-reversible with on-board energy storage) have over the that final operation cost.

4.2 Outline

The present chapter will concur as follows: initially a presentation of the case of study is performed, where the main characteristics of the system infrastructure, rolling stock and operation of the same are presented. Following to that, a methodology to selected the optimal contracted power for the case of a railway system is developed in detail accompanied by empirical conclusions obtained for the case study. Different traffic densities have been considered as well as the possible system failures that can occur. Additionally, the correspondent validations of the method with a commercial optimization tool are presented. The last part of the chapter, once the method development is concluded, is based on evaluating the impact on the network and, therefore, on the bill to pay of adding energy storage systems both at substation level and on-board.

4.3 Case of Study: Malaga-Fuenguirola-Alora

4.3.1 Feeding infrastructure

The case of study in this section will focus on the study of a real network located in the south of Spain. It is a commuter rail service between central Malaga and towns in the province. There are two lines of 30.84km (red line) and 36.93km (blue line). The trains are powered by overhead lines with a voltage level of 3000 V. The simplified diagram of the network is depicted in Fig 4-1. The blue railway line has 9 stops and 4 electrical nodes labelled as S1, S2, S3 and S4. The red line shares the first two electrical nodes with the blue line and it has 17 stops and 6 electrical nodes labelled as S1, S2, S3, S4, S5 and S6. Nevertheless, among the cited nodes there are only 3 feeding substations while the rest of them are disconnected from the grid (AC side). The three substations are placed in nodes S3 and S5 of the red line and in node S3 of the blue line.

All the substations have the same electrical design: they are connected through a power transformer of 3 MW with a short circuit voltage of 5%. The output voltage of the rectifier under no-load conditions is of 3000 V and at rated load (1000A) of 2880 V. The equivalent impedance in each of the three substations in forward mode is $270m\Omega$. When accumulators are added to the feeding substations, each accumulator will have a maximum energy capacity of 50kWh and a maximum charge and discharge power of 2MW. Parameters V1, V2, V3 and V4 are set respectively to 2685V, 2985V, 3015V and 3315V while parameters SOC1,2,3 and 4 are 0%, 10%, 90% and 100%. The efficiency of the charging and discharging process is assumed in 95%.

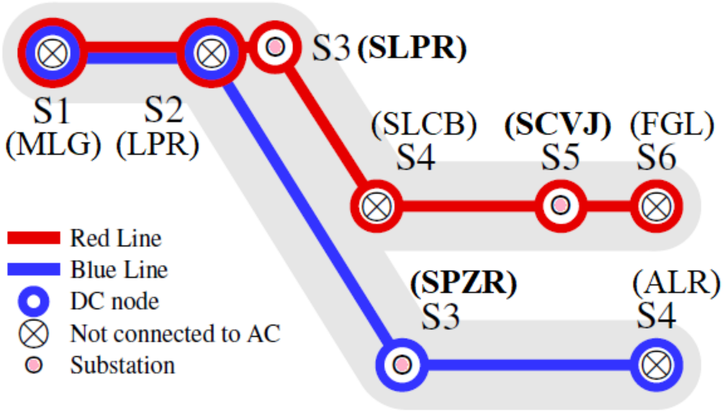


Figure 4-1: Schematic representation of the case of study [2].

4.3.2 Rolling stock

It will be used the same units in both lines. The whole train is a 2.940m wide, 4.265m high and 98.05m long unit, with a weight of 157.3t. The used train is a multiple unit formed by 5 cars, where the first and last one allocate the driver's cabin and normal floor. The car in the middle has also a normal floor, while the other two have a low floor. Both the trailer bogie and the tractor bogie support all the cars. The tractor bogie is always shared between two cars. The track for which the vehicle is designed is an Iberian track gauge type (1668mm). The maximum speed will be 120 km/m with 1000 passengers. The maximum power of the train is 2.2MW and it has regenerative braking capability. An electromechanical efficiency of 95% for both traction and breaking mode is considered.

The minimum and regulation voltages of the train during traction mode were set to 1980V and 2280V (V1; V2) for the configuration of the protection curves and storage devices. The maximum regulation voltages and maximum voltage for squeeze control during braking mode (V3; V4) were set to 3300V and 3600V. The on-board battery features are: an efficiency of 95% , maximum energy capacity of 10kWh and a maximum charging and discharging power of 1MW.

4.3.3 Simulated scenarios description

Different scenarios to study the influence of the traffic density on the optimum power to be contracted have been simulated and analysed. There are two lines: S1 to S6 (red line) and S1 to S4 (blue line). Two different traffic densities have been taken into consideration. Light traffic scenarios use a train headway of 45 minutes with 48 departures (24 in the outbound and 24 in the return route) in the red line and of 60 minutes with 36 departures (18 in the outbound and 18 in the return route) in the blue line. Heavy traffic scenarios use a train headway of 15 minutes with 138 departures (69 in the outbound and 69 in the return route) in the red line and of 20 minutes with 104 departures (52 in the outbound and 52 in the return route) in the blue line. The simulation interval is very similar for all scenarios: in heavy traffic starts at 5:30 a.m whereas in the light traffic at 6:00 a.m. Both of them are simulated the whole day, around 17 hours of operation. These base scenarios have been simulated firstly without on-board and off-board accumulators and non-reversible substations in order to propose a methodology to select the optimal contracted capacity. Later, modifications over these base case are done to compare the different technologies.

4.3.4 Optimization of the contracted power: methodology basis

As previously introduced, to compute the bill, the instantaneous power is not of interest, but the average power registered by the meter in 15-min blocks. The maximeter works taking note of the power being demanded and does so in 15-minutes blocks. For each of these blocks, it calculates the average power required in that specific period of time.

To perform an optimization, it will be essential to obtain the highest demanded power in each substation. Therefore, it is necessary to know the maximum registered averaged power by the maximeter as shown in the previous section. This data is shown in Table 4.1 for he case of study under a light traffic scenario.

Light traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[500.5905, 566.1744, 519.3856]	kW
Degraded case for SCVJ	[- , 815.5025, 575.1875]	kW
Degraded case for SLPR	[738.6149, - , 828.9332]	kW
Degraded case for SZPR	[601.5279, 991.2538, -]	kW

Table 4.1: Maximum registered averaged power by the maximeter for the case of light traffic.

It should be noted that the Spanish RD 1164/2001 dictates that *"the powers contracted in the different periods will be such that the power contracted in a tariff period (Pn+1) is always greater than or equal to the power contracted in the previous tariff period (Pn)"*. That is, it must always be true that $P_{C1} \leq P_{C2} \leq P_{C3} \leq P_{C4} \leq P_5 \leq P_{C6}$.

Due to this restriction and with the intention of simplifying the optimization method, the same contracted power will be considered in the six time periods.

It is important to remark that the power prices given by the Spanish regulation in the case of the power term (see Tables 3.4 and 3.6) are final prices, that is the total price that later is used to compute the bill. That, however, is not equal for the energy term, which is compound by two parts: a fixed part given by the regulation (see Tables 3.5 and 3.7) and a variable part that depend on the utility. This variable part will depend on many factors and it is a totally confidential information. Therefore, to perform the analysis a term five times greater than the regulated term is used. It is considered that it could be a quite accurate approximation for these type of clients.

Method 1: Same contracted power in all periods and for all substations

The power to contract will be chosen based on two criteria:

a) The first criterion is based on taking only into account the needs for the normal operation of the system and, therefore, the contracted power is selected to cover the maximum demand under that circumstances. In this case, the highest power recorded by the maximeter is in the substation *SLPR*. Hence, a contracted power of 650 kW has been selected.

b) The second criterion, on the contrary, is a more conservative method and it is based on contracting a power that covers the worst case that can occur in the system. It is considered that in the worst case one out of the three feeding substation may have a fail and the system will be operating with the two other substations. In this case, a contracted power of 1200 kW has been selected, that would cover the worst of the degraded cases, which occurs in the substation *SCVJ*.

It should be noted that it is introduced a small margin of around the 15-20% when selecting the powers to be contract.

Fig. 4-2 shows the total operation cost per year in each of the possible situations (normal operation and degraded cases) when a contracted power of 650 kW is applied. While in Fig. 4-3 the same results are shown for a contracted power of 1200 kW. Comparing both figures, it can be easily deduced that the criterion of this method is based on avoiding the power penalty term: in the first case for normal operation and in the second for any of the degraded situations that may occur in the system. Therefore, the first case is based on optimizing the contracted power for most of the time, that is normal operation, while the second is intended to avoid having high peaks of economic penalties occasionally.

Therefore, in conclusion, the choice of the first method would imply high economic penalties when an excess of power demand occurs in the system, while the second method avoids having penalties under any circumstance, but it comes with the price of having to pay bill a quite higher bill during the normal operation of the system, which should generally be most of the time.

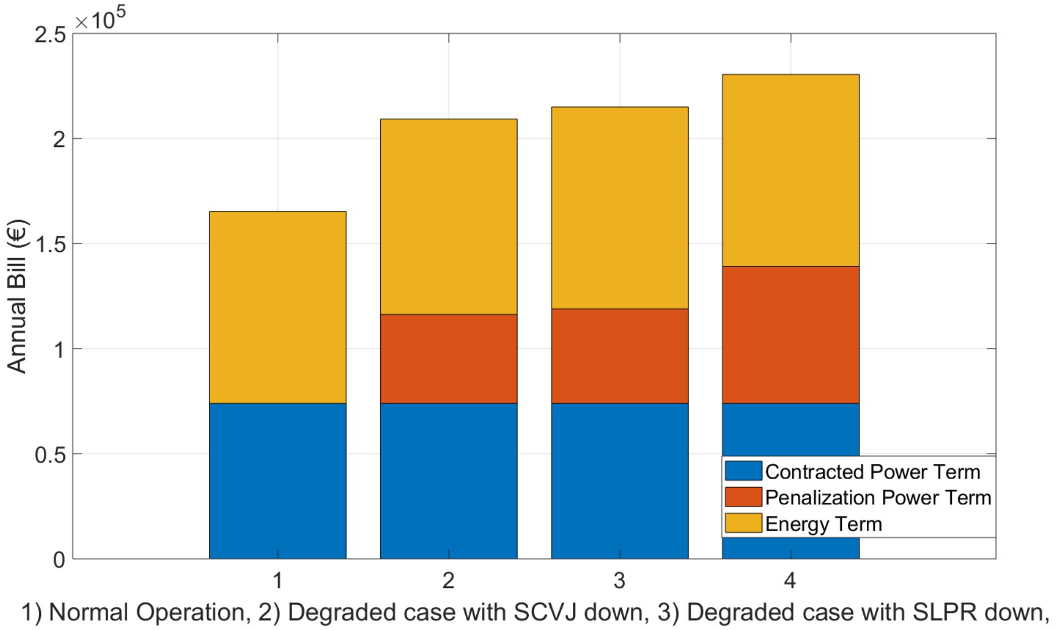


Figure 4-2: Annual operation cost of the whole system for a contracted power of 650 kW in all time periods with a 6.4 access rate for the light traffic scenario.

According to the results shown in Table 4.2, the bill will increase by 24.3% on average when a degraded situation occurs under the first scenario methodology of hiring the lowest possible power to cover the highest demand for normal operation. On the contrary, according to the data in Table 4.3, if a higher contracted power is selected, when a case of degradation occurs, the invoice on average is practically unaffected (<1%).

However, as we have already discussed, choosing a higher power comes at the cost of increasing the bill in normal operation. In this case, it can be seen that in the second case the total invoice increases by 27.5% compared to the first case in normal operation.

It should be noted that with the intention of simplifying the conclusions and

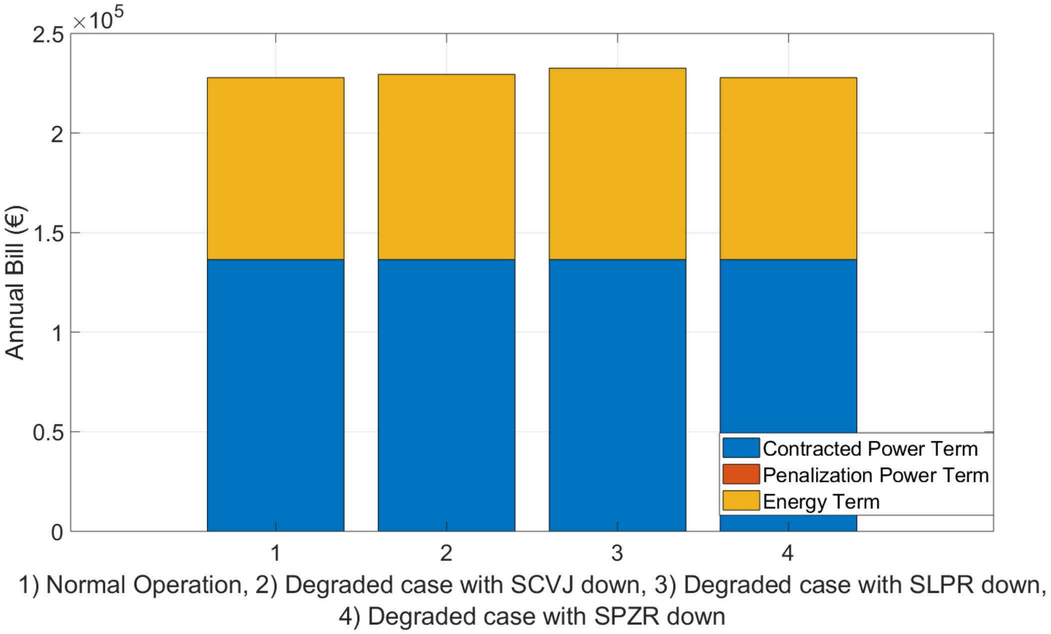


Figure 4-3: Annual operation cost of the whole system for a contracted power of 1200 kW in all time periods with a 6.4 access rate for the light traffic scenario.

Light traffic scenario	**Annual Bill**	**Units**
Normal Operation	165,278.01	€
Average of the degraded cases	218,244.65	€

Table 4.2: Total bill per year under different scenarios in the case of light traffic with a contracted power of 650 kW.

Light traffic scenario	**Annual Bill**	**Units**
Normal Operation	227,837.43	€
Average of the degraded cases	229,957.17	€

Table 4.3: Total bill per year under different scenarios in the case of light traffic with a contracted power of 1200 kW.

obtaining a standard method for choosing the optimal contracted power, the degraded cases are not considered individually, but average of all of them is obtained.

At this point, after having analysed the implications of both methods, the question is which method is more economically profitable for the company. However, this question does not have a direct solution, but will depend on the total time that the system is in a degraded situation (it has a substation out of service) and, therefore, the other two substations have to cover that extra demand.

Following, the proposed method for calculating the intersection point where both operating options have the same cost ($C1 = C2$) is presented. Thus, beyond that point (which is the total average minutes of failure per year considering all the power supply substations) the second option (b) will be more profitable while, below that point, the first option (a) will be more profitable.

$$\begin{aligned} C1 = m \cdot C1_{\text{degraded cases}} + (t - m) \cdot C1_{\text{normal operation}} = \\ m \cdot 218,244.65 + (525600 - m) \cdot 165,278.01, \end{aligned} \tag{4.1}$$

$$\begin{aligned} C2 = m \cdot C2_{\text{degraded cases}} + (t - m) \cdot C2_{\text{normal operation}} = \\ m \cdot 229,957.17 + (525600 - m) \cdot 227,837.43, \end{aligned} \tag{4.2}$$

where m is the total number of minutes per year on average in which the system has any substation out of service, t are the total minutes that has one year and the costs $C_{\text{degraded cases}}$ and $C_{\text{normal operation}}$ are the ones presented in Tables 4.2 and 4.3.

From the results shown in Fig. 4-4, it can be concluded that the second option would only be economically more profitable if the failures in the system's substations were maintained for 450 days, that is, more than one year which is a non-realistic situation. Therefore, to optimally select the contracted capacity of the system the degraded case that can occur must be not taken into account and only the normal operation of the system has to be considered.

Method 2: Same contracted power in all periods, but different in each substation

This second method follows exactly the same criteria as the first, but the contracted power will be chosen individually for each of the substations instead of selecting the worst case scenario for the entire system. According to this criterion, the contracted

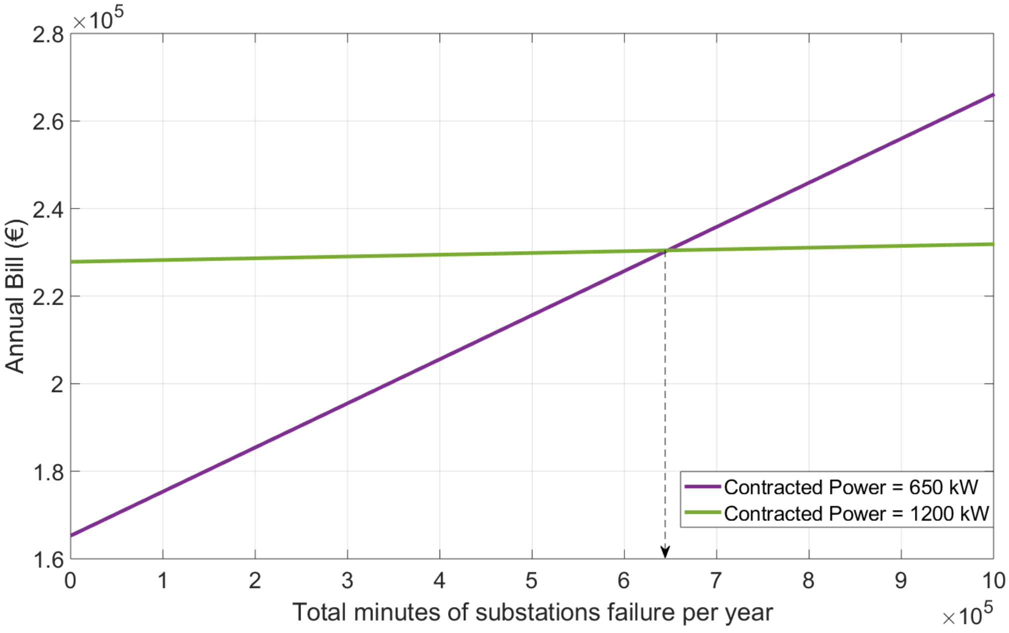


Figure 4-4: Annual operating costs versus average minutes of substation failure in the system when the same contracted power is selected for all the feeding substations.

power for the first case will be 580 kW for the substation *SCVJ*, 650 for *SLPR* and 600 kW for *SPZR*. And, for the second case will be 850 kW for the substation *SCVJ*, 1200 for *SLPR* and 950 kW for *SPZR*.

Fig. 4-5 shows the total invoice per year in each of the possible situations (normal operation and degraded cases) when a contracted power of [580, 650, 600] kW is applied. While in Fig. 4-6 the same results are shown for a contracted power of [850, 1200, 950] kW.

According to the data in Table 4.4, the bill will increase by 28.1% on average when a degraded situation occurs under the first scenario of hiring the lowest possible power in each of the substations. On the contrary, according to the data in Table 4.5, if a higher contracted power is selected, when a case of degradation occurs, the invoice is practically unaffected (1%).

However, as it has been already discussed, choosing a higher power comes at the cost of increasing the bill in normal operation. In this case we see that in the second case the total invoice increases by 21.6% compared to the first case in normal operation.

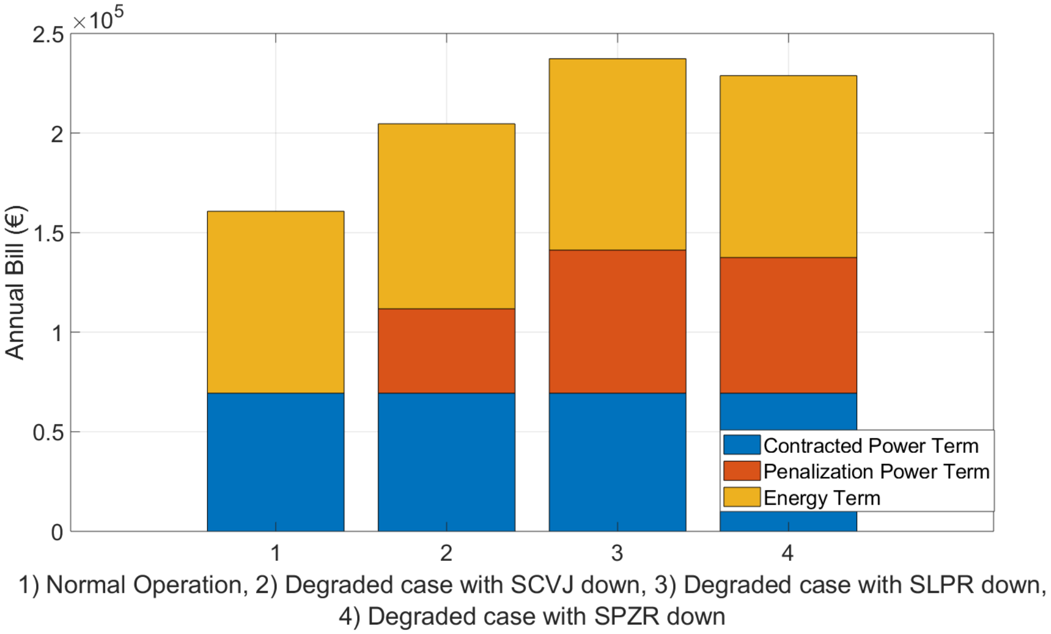


Figure 4-5: Annual operation cost of the whole system for a contracted power of [580, 650, 600] kW in all time periods with a 6.4 access rate.

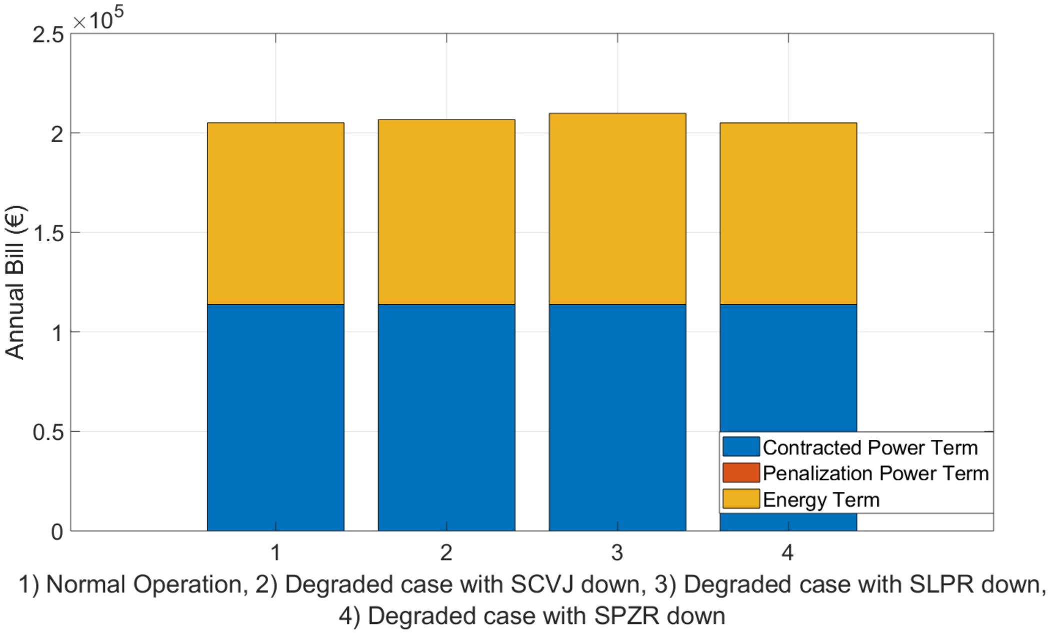


Figure 4-6: Annual operation cost of the whole system for a contracted power of [850, 1200, 950] kW in all time periods with a 6.4 access rate for the light traffic scenario..

Notice that the bill is reduced in both cases (option a and b) by a 3% and 10% respectively using the method 2 compared to method 1, which thereby makes

Light traffic scenario	**Annual Bill**	**Units**
Normal Operation	160,728.24	€
Average of the degraded cases	223,607.20	€

Table 4.4: Total bill per year under different scenarios in the case of light traffic with a contracted power of [580, 650, 600] kW.

Light traffic scenario	**Annual Bill**	**Units**
Normal Operation	205,088.55	€
Average of the degraded cases	207,208.29	€

Table 4.5: Total bill per year under different scenarios in the case of light traffic with a contracted power of [850, 1200, 950] kW.

clear that to select the contracted power taking into account each feeding substation requirements leads to a reduction in the bill.

It should be highlighted that due to the selected train timetables it coincides that in the light traffic scenario the three feeding substations have almost the same demand, which makes that the price differences obtained between method 1 and 2 in normal operation are not so relevant. However, in most of the cases the substations demands will differ considerably from each other and it will be much more evident the savings obtained as a result of individually address each substation instead the system as a whole. For example, in that same network, if the train headway in both lines is changed to 50 minutes, the demand in the substation *SPZR* is almost half than in *SLPR*. That permits to select quite different contracted capacity in each substations and the savings go over the 20% when comparing normal operation between method 1 and 2.

Finally, in the same way than in the previous method, it is necessary to calculate the total time in which the substations must be in a degraded case so that the second option is more profitable than the first, in this case, as shown in Fig. 4-7, the time is reduced to half, about 260 days. Even so, it is an average failure time much higher than the failure times recorded in real cases. Therefore, with that second verification, it is clear that contracting a capacity higher than the requested for normal operation in order to not obtain penalties if a degraded case occurs is no economically profitable.

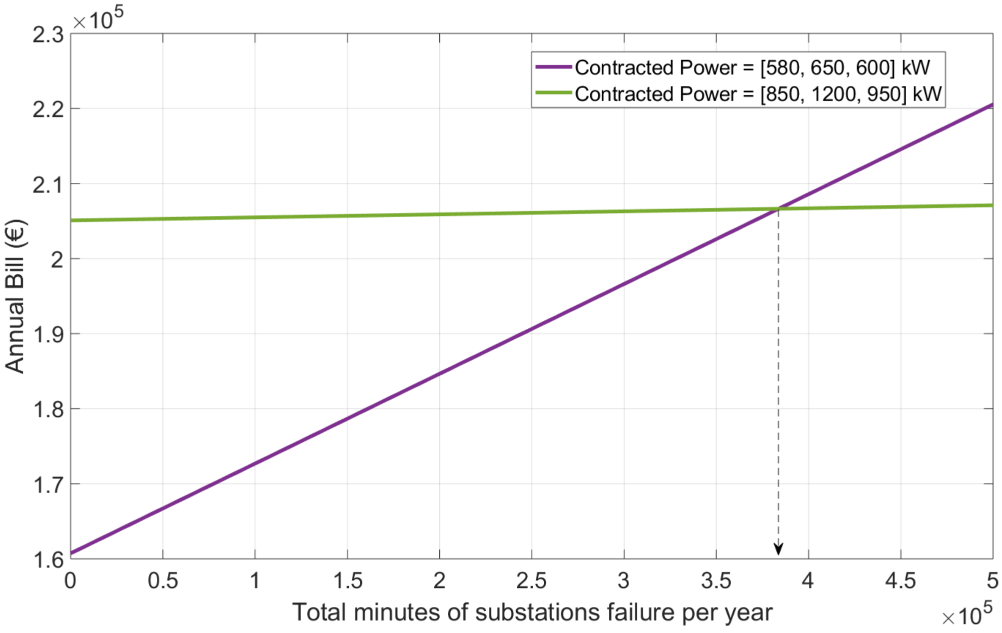


Figure 4-7: Annual operating costs versus average minutes of substation failure in the system when a different contracted power is selected in each of the feeding substations.

4.3.5 Optimization of the contracted power: validation of the proposed method with MatLab's 'fmincon' optimization tool

In the previous section, it has been concluded that the optimal power to contract would be the highest power recorded by the maximeter in normal operation in each of the feeding substations. Even so, it should be noted that this conclusion has been proposed without using optimization algorithms that will try a wide combination of contracted powers. However, below, with the help of the *Matlab* program optimization tools (by using the word 'optimization' in MatLab we refer to the process of searching for the minimum or maximum of a function) the validation of the previous conclusion will be demonstrated.

This tool will allow not only to validate the proposed method, but also will corroborate that the simplification made by not taking into account a different power contracted for each time period (P1 to P6), but the selected one is the same for all of them, is totally acceptable.

Therefore, the aim of this optimization is to find the minimum scalar value returned by a non-linear function (that is the annual electricity bill). To obtain so the it is required to optimize the contracted power per time period (P_{C1} to P_{C6}) subject to the restrictions stated by the country regulations (in this case, by the 1164/2001).

The tool *fmincon* finds the minimum of a constrained non-linear multivariate function specified by:

$$\min f(x) \text{ such that } \begin{cases} c(x) \leq 0 \rightarrow \text{non-linear inequality constraints} \\ ceq(x) = 0 \rightarrow \text{non-linear equality constraints} \\ A \cdot x \leq b \rightarrow \text{linear inequality constraints} \\ Aeq \cdot x \leq beq \rightarrow \text{linear equality constraints} \\ lb \leq x \leq ub \rightarrow \text{lower and upper bounds} \end{cases} \tag{4.3}$$

In this case to configure that module there has been only used the non-linear inequality constraints defined by (3.1) as shown in Fig. 4-8. The function to optimize is the function 'Results.m', in which the annual bill of the system is computed, presented in section 3.4.

In Table 4.6, there are shown the contracted power optimization results obtained for each feeding substation and time period. It is clear that these powers coincide with the powers registered by the maximeter previously exposed in Table 4.1 (since the validation has been done under the light traffic scenario).

	SCVJ	**SLPR**	**SPZR**
P_{C1} (kW)	500.59	566.17	519.39
P_{C2} (kW)	500.59	566.17	519.39
P_{C3} (kW)	500.59	566.17	519.39
P_{C4} (kW)	500.59	566.17	519.39
P_{C5} (kW)	500.59	566.17	519.39
P_{C6} (kW)	500.59	566.17	519.39

Table 4.6: Optimal contracted power per time period for the light traffic scenario obtained with optimization tool *fmincon*.

```matlab
%Solve the OPF problem
A=[]; Aeq=[]; b=[]; beq=[]; lb=[]; ub=[]; %There are not lineal equalities or inequalities or boundaries
options=optimset('Display','Iter'); %Specified optimization options (by defect)
[SOL,fval,exitflag,output,lambda,grad,hessian]=fmincon(@myfun,X0,A,b,Aeq,beq,lb,ub,@mycon,options); %'SOL' will return the matrix with the optimal contracted power per time period
%Define the constraints of the OPF problem
function [c ceq] = mycon(X)
    Pcontracted = X;
    c = zeros((size(Pcontracted,1)-1)*size(Pcontracted,2),1); % define inequalities: P_c1 <= P_c2 <= P_c3 <= P_c4 <= P_c5 <= P_c6
    idx = 1;
    for n = 1:size(Pcontracted,2) %Loop over the nodes
        for k = 1:size(Pcontracted,1)-1 %loop over the time periods
            c(idx)=Pcontracted(k,n)-Pcontracted(k+1,n);
            idx = idx + 1;
            c(idx) = 100-Pcontracted(k,n); %A minimum of a contracted power of 100 kW has been established
            idx = idx + 1; %
        end
        c(idx) = 100-Pcontracted(k,n);
        idx = idx + 1;
    end
    ceq = []; %There aren't inequalities. The way to say so is to let an empty vector.
end
```

Figure 4-8: *Fmincon* function configuration used.

The obtained results, as previously introduced, not only validate the method, but also it is clear that to assume a non multi-variable problem does not have impact on the results. In this case, the trains timetables are equally spaced in time and, therefore, the same demand profile is repeated during the whole simulation interval. Nevertheless, in reality most of the times the train timetables are also configured like this (for a better reminder of the customers) or even, the frequency of trains is increased at peak times, which thereby reinforces the idea of simplifying the problem and transform the constraints to a non-linear equality constraints ($P_{C1} = P_{C2} = P_{C3} = P_{C4} = P_{C5} = P_{C6}$).

Notice that in the previous section it is indicated that the contracted power will not be adjusted to the limit, but an upper margin around the 20% will be always established. Railway operators are in charge of a public service and always will let a conservative margin.

The use of commercial optimization tools such as *fmincon* allows to greatly reduce the computational time since it uses advanced optimization algorithms appropriate to the problem. However, it has the drawback of not being an open source tool, which would imply that, if it is intended to make such optimization by the company, it should use its own equivalent algorithm.

Following, it is demonstrated that defining a wide power sweep range for each substation and computing the bill for each of those possibilities return the same results than the ones obtained with *fmincon*. Although this method is much more simpler, the computation time is much more longer and, moreover, it considerably limits the precision with which the problem is solved. In this case a step 10 kW have been set to solve the optimization. Additionally, the implemented method does not solve multi-variable problems.

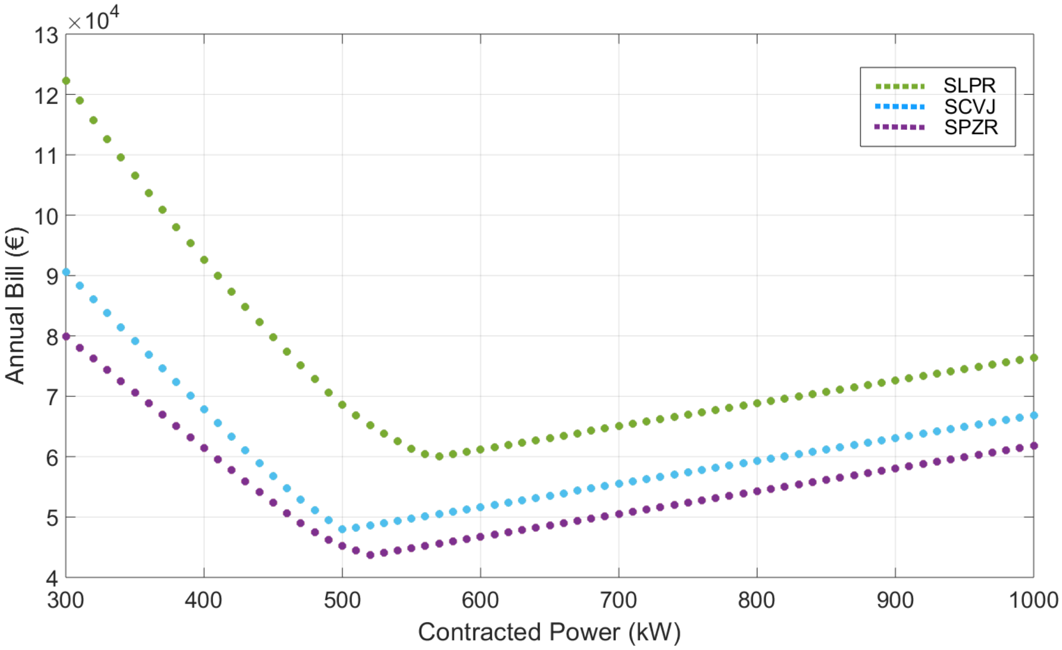


Figure 4-9: Optimal contracted power for the light traffic scenario obtained with a power sweep method.

4.3.6 Optimization of the contracted power: different traffic scenarios evaluation

Up to now, the work has been only focused on developing a method that allows to determine the manner of selecting the optimal contracted power of a system. It has been evaluated if it is profitable to increase the contracted power in the different substations in order to cover the cases in which a fault occurs in any substation as well as if it is interesting to evaluate each substation individually or the system as a whole.

However, the different traffic profiles that the system will have to support within a year have not been considered.

In Fig. 4-10, it can be seen the large increase in the bill if the same contracted powers - [500, 600, 400] kW - are considered to compute the bill under the heavy traffic scenario than for the light one (see Fig. 4-5).

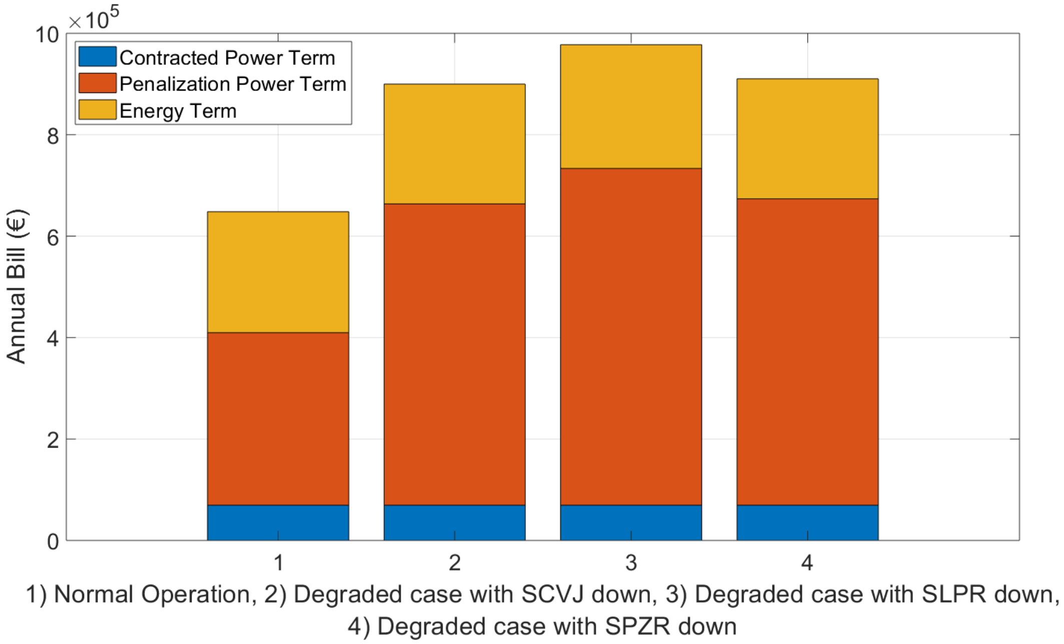


Figure 4-10: Annual operation cost of the whole system for a contracted power of [580, 650, 600] kW in all time periods with a 6.4 access rate for the heavy traffic scenario.

Nevertheless, it is essential to bear in mind that up to this point when computing the annual bill it has been considered a full year with a single traffic profile. However, this approach is not realistic at all since in one full year a few different traffic profiles will coexist. For example, a traffic profile could be set for working days and another for weekends and holidays.

Therefore, from the above mentioned it is deduced the need of establish a method to determine which is the number of days per year of high traffic that are necessary for increasing the contracted power in order to avoid penalizations and get a bill as low as possible. Notice that this has a correlation with the need of computing the point in which is profitable to consider the degraded case to correctly choose the contracted power (see Figs. 4-4 and 4-7).

Similarly to the evaluation performed for the light traffic scenario, in Table 4.7 it is shown the maximum average powers recorded by the maximeter in the case of heavy traffic.

Heavy traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[822.0616 , 1091.3339, 755.4878]	kW
Degraded case for SCVJ	[- , 1740.8881, 899.8202]	kW
Degraded case for SLPR	[1414.9961, - , 1300.1861]	kW
Degraded case for SZPR	[963.2291, 1665.9296, -]	kW

Table 4.7: Maximum registered averaged power by the maximeter for the case of heavy traffic.

In section only average calculations have been used to evaluate the influence of the degraded cases. That is because the probability of failure of a substation is estimated to be a constant function, which means that there are the same probabilities that any of the substations fail throughout year. Hence, this failure rate allows to estimate the effect that this will have on average on the bill.

Nevertheless, it must be clear that does not have the same economic impact that a substation fails at peak hours (i.e. 10 a.m) that in off-peak hours (i.e. 3 a.m). But, as stated above there is no way to predict when a fail will occur and, therefore, mean values are used.

That situation, however, changes when evaluating the different traffic scenarios impact since the train timetables are known in advance of the start of operation. As introduced from the beginning of the chapter it is of a great importance the difference of prices of power and energy at peaks hours respect to the off-peak ones and, therefore, the heavy traffic penetration will not have the same consequences along the day.

Therefore, it is required to evaluate the number of days of penetration of heavy traffic in the base case of light traffic from which the contracted power must be heightened to avoid large penalizations and thus, an unnecessary increase in the bill. To assess that number of days, three different "type days" have been evaluated. This is because the different divisions done by the regulation can roughly be differentiated into three types: where mainly the most expensive periods appear (P1 and P2), where mainly the intermediate periods appear (P3 and P4) and where only the cheapest periods appear (P5 and P6 or even only P6). As shown in Fig. 3-1 these are the penetration of high traffic in July (it would represent the most expensive month of the year), March (it represents an intermediate month in terms of costs) and on weekends and holidays (it would represent the cheapest days).

It would be of interest to evaluate mixed profiles along the day (not equidistant train timetables), however, as a first approach only full-day traffic profiles are considered: light and heavy or high. In this case, these two profiles differ quite from each other, which quickly makes the high traffic profile predominate. However, if there are several traffic profiles, as just introduced, it is less evident the impact of each of them and, therefore, to correctly select the optimal capacity could not be an immediate and obvious decision and this study becomes essential.

To sum up, there is the need to solve the question of how many days of penetration of high traffic are needed for being profitable to increase the contracted powers and avoid large penalizations. The answer will mainly depend on two factors: in which type day (or month of the year) occurs that penetration and, therefore, in which time period (P1 to P6) occurs and how many times or days that takes place.

High traffic penetration in July

Firstly, it will be evaluated the effect of the penetration of high traffic in the most expensive type days of the year (second fortnight of June and July). To do, it is computed the total bill using the optimal contracted powers for light traffic - [580, 650, 600] kW - and the optimal contracted powers for high traffic - [950, 1300, 900] kW -. In Fig. 4-11, it is depicted the evolution of the annual bill as the number of heavy traffic days grows. The shaded part of the graphic represents the different parts of the bill evolution when that penetration occurs with the optimal contracted powers for light traffic. Additionally, a red line is plotted to show the evolution of the bill if optimal contracted powers for heavy traffic are chosen. That red line from the beginning is much higher than the shaded part because of the difference in cost due to the contracted power term. Moreover, notice that the price accumulated from contracted power and energy terms is parallel to the price accumulated with high contracted powers (red line). Therefore, the price difference evolution comes from the power penalization term.

In conclusion, the intersection point shows the number of days from which is more profitable to increase the contracted powers than to pay penalizations since, at this point, the penalizations are higher than the cost difference between contracted power terms. In this particular case, the results are that around 30 days of penetration are required for being beneficial to increase the contracted powers in all periods up to the point of covering the heavy traffic demand.

High traffic penetration in March

Previously in this section, it was mentioned the assumption of contracting the same power in all the time periods (P1 to P6) due to the fact that the Spanish regulation does not allow to do allow changes in the contract within a year and, in addition, because the nature of railway operation is always to be more intense at peak hours (when people come and go work, universities, etc).

However, if peak demands occur in type days in which the most expensive periods (P1 and P2) does not appear as could be the case of a month in which the train timetables are increased for a local festivity, it could be evaluated the option of increasing the contracted powers only in the required periods. This strategy may be more profitable since the contracted power price for that periods is much lower

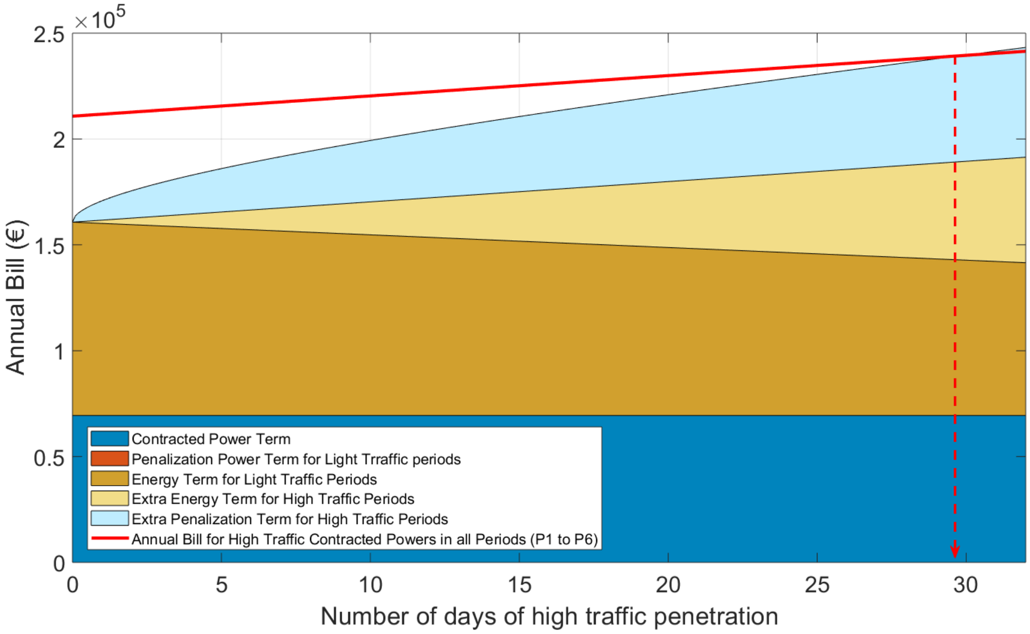


Figure 4-11: Annual bill with contracted powers of [580, 650, 600] kW vs. with contracted powers of [950, 1300, 900] kW for different high traffic penetrations in July type days.

and, therefore, it may be more beneficial to increase a bit the contracted power term instead of paying penalizations.

The above exposed, can be clearly seen in Fig. 4-12. When performing a penetration of days of high traffic in day types of medium price (March, first fortnight of June, September and November), it quickly compensates (around 20 days) to increase the contracted powers for periods P3 to P6, but if the contracted powers must be increased in all the periods up to 75 days still more profitable to maintain the contracted powers for the light case and pay some penalizations.

This demonstration shows that to evaluate individually each case of study and its different traffic scenarios can clearly provide significant reductions in the operation cost that over the years it could become a favourable distinction between railway operators.

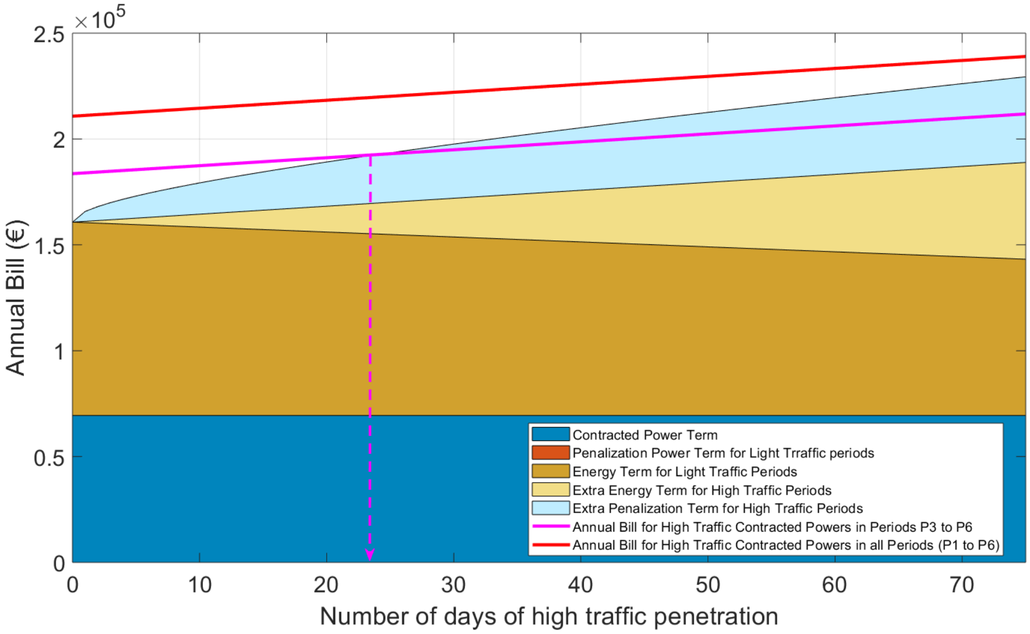


Figure 4-12: Annual bill with contracted powers of [580, 650, 600] kW vs. with contracted powers of [950, 1300, 900] kW for different high traffic penetrations in March type days.

High traffic penetration in weekends & holidays

Finally, it has been evaluated the impact of introducing heavy traffic days in the cheapest days types where only there is P6 (August and weekends & holidays).

In Fig. 4-13, it can be seen the results of that penetration and it can be rapidly concluded that in this case it compensates from the very beginning to increase the power in P6 to compensate the heavy traffic demand instead of having any penalization. That is because the increase in the contracted power term is really insignificant, nonetheless, if the contracted must be increased in all the periods to cover that type days, it absolutely does not compensate because the contracted power term is much more significant that the penalizations suffered in that period.

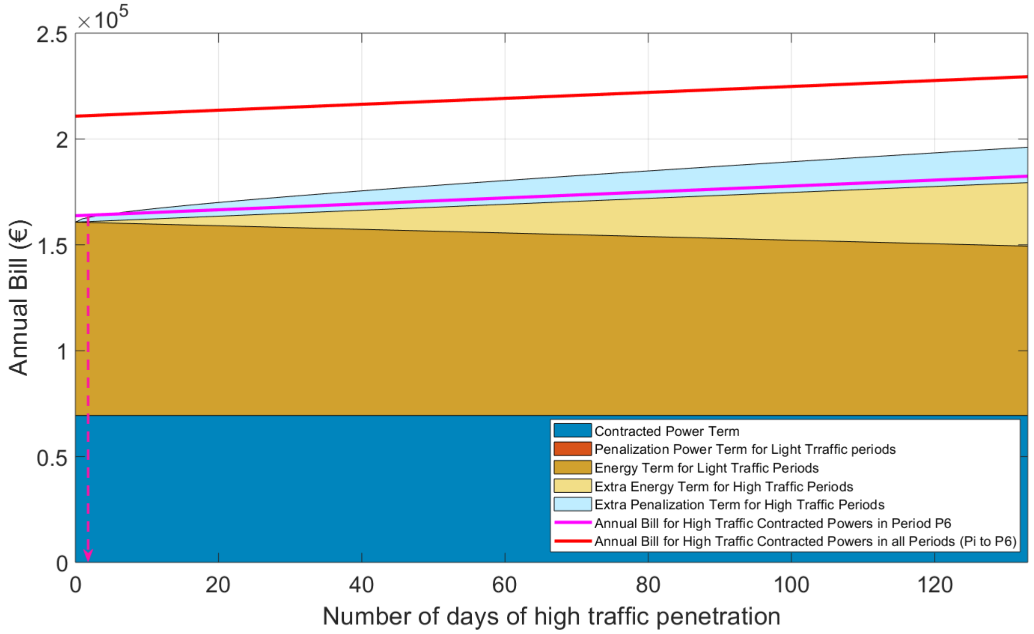


Figure 4-13: Annual bill with contracted powers of [580, 650, 600] kW vs. with contracted powers of [950, 1300, 900] kW for different high traffic penetrations in weekends & holidays type days.

4.3.7 Optimization of the contracted power: different traffic scenarios impact validation with MatLab's 'fmincon' optimization tool

As well as it was evaluated the correct performance of the exposed methodology to select the optimal contracted power of a railway system with commercial optimization tools (in this case, with the optimization toolbox of MatLab), now, this is done again to prove that the mentioned conclusions under different scenarios are correctly obtained.

Equally than the tests described in section 4-8, now, they are done again, but, introducing the influence of the heavy traffic penetration.

In Fig. 4-14, it is shown the optimal contracted power evolution depending on the heavy traffic penetration for the most expensive type days and how around the 30 days od penetration the optimal contracted power goes from the optimal contracted power for the light traffic scenario to the optimal to cover the heavy traffic scenario (around double in all the substations).

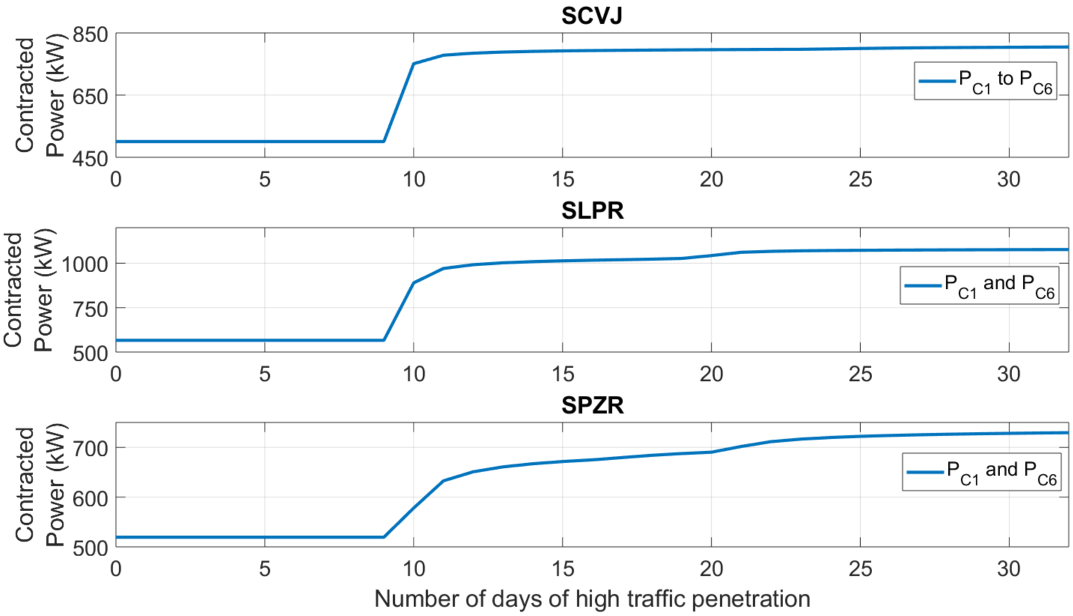


Figure 4-14: Optimal contracted powers for different high traffic penetrations in July type days (most expensive) obtained with the optimization tool *fmincon*.

In Figs. 4-15 and 4-16, the optimal contracted powers evolution with the heavy traffic penetration again match with the previous conclusions. In Fig. 4-15, it can be seen that it is profitable to rise the contracted powers from period P3, however, if all the periods must be risen, it is more profitable to pay certain penalization in these periods. Also, similar conclusions are obtained from Fig. 4-16, where from the beginning is better to increase the contracted power in P6, but, if the contracted powers in all the periods must be increased, it is utterly more beneficial to maintain the contracted powers in a lower value.

4.3.8 Optimization of the contracted power: impact of energy storage systems

Up to this point, a deep analysis on the different scenarios that can have an influence on the decision of which is the optimal contracted power for a railway system have been performed. Nevertheless, the whole evaluation has been done on a base case in

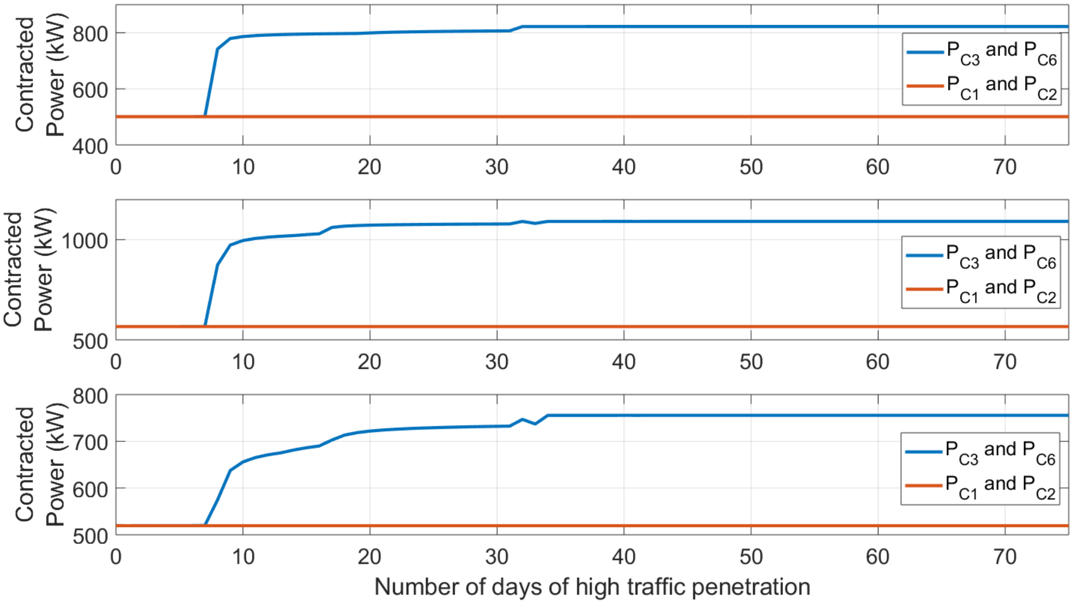


Figure 4-15: Optimal contracted powers for different high traffic penetrations in March type days obtained with the optimization tool *fmincon*.

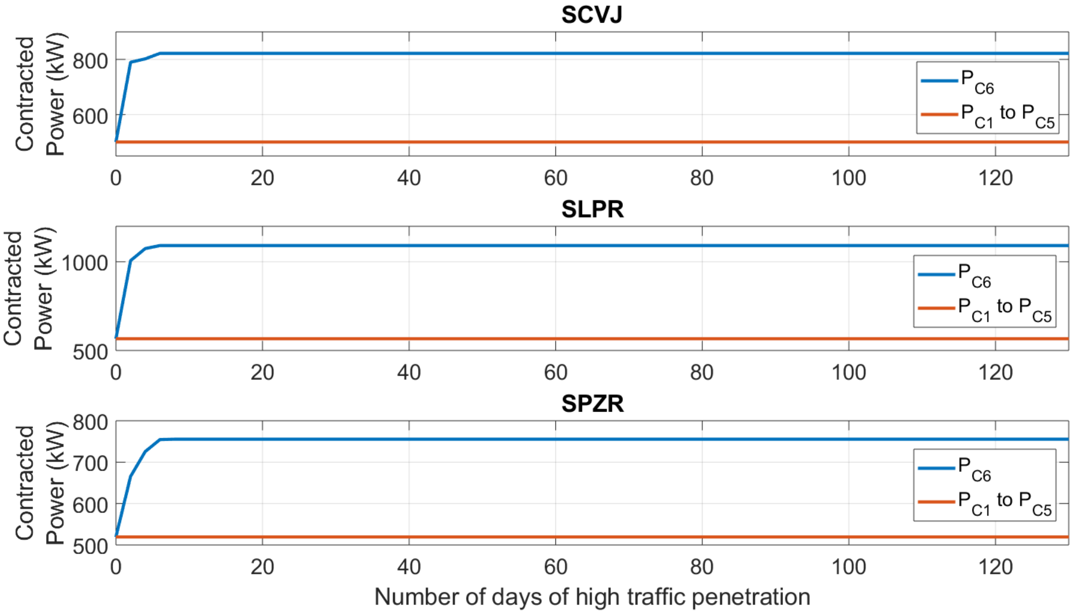


Figure 4-16: Optimal contracted powers for different high traffic penetrations in weekends & holidays type days (cheapest) obtained with the optimization tool *fmincon*.

which only non-reversible substations without any energy storage capability have been considered. That also applies to the trains, there has not been added any accumulator to those. In consequence, in a last module, it has been asses the influence that can have on the cost to add batteries, both off-board in the feeding substations and on-board on the trains.

Since in the present work only the cost due to electric variables is considered, two factors must be evaluated in order to check the influence of adding ESSN and ESST. On the one hand, it has been concluded that the power contracted term will depend on the maximum power peak taken by the maximeter (average power in 15-min blocks) and, therefore, it has to be check if the accumulators will help to lower that maximum power peak. If so, the operator will be able to select a lower contracted power and, therefore, that fixed cost will be smaller. On the other hand, it has to be analysed if with accumulators the energy demand is lowered. Consequently, if that happens, the energy term to pay will drop.

Off-board energy storage systems (ESSN)

Firstly, one battery (which characteristics are described as the beginning of the present section) has been added to each of the feeding substations.

To start with the analysis, it has been done a comparison between the maximum power peak taken by the maximeter in order to analyse if it is possible to lower the contracted power term. In fig. 4-17, it can be seen the average power registered along a whole day (96 periods of 15-min) in each of the feeding substations. It can clearly be seen that the dotted lines, which represent the cases with ESSN, are lower in all the cases than in the cases without storage capability represented by a continuous line. More specific results can be found in Table 4.8. The conclusion is that those power peaks are reduced in average around a 7% in the system of study.

It is remarkable that these comparison on the power profile have been done with different initial SOCs and the results show that there is no difference between starting the operation with ESSN with a initial SOC of the 0% or of 100%. That is because at the beginning of the simulation, the grid voltage is high and the traffic is low and, therefore, the battery always is charged in that first part and later, the charging and discharging process is regular and equal independently of that initial SOC. A deeper analysis on the battery control should be done to obtain a greater number of conclusion on that point.

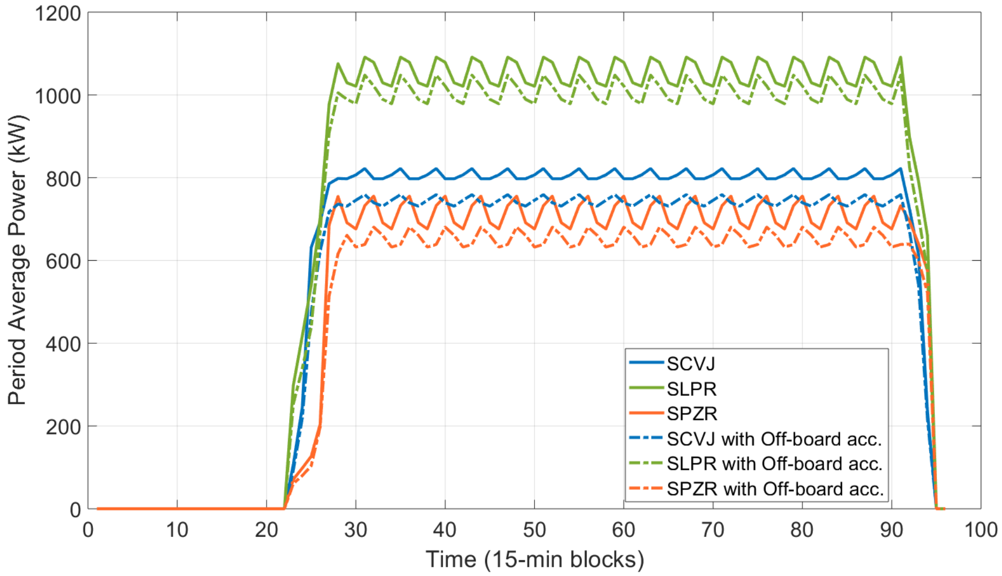


Figure 4-17: Period average power (15-min blocks) registered by the maximeter comparison for th case of heavy traffic with and without ESSN.

Heavy traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[822.1, 1091.3, 755.5]	kW
Normal Operation with off-board accumulators	[759.1, 1047.9, 680.5]	kW
Average maximum power peak reduction	**7.19**	%

Table 4.8: Maximum registered averaged power by the maximeter for the case of heavy traffic with and without ESSN.

A similar analysis has been done to compare the energy demand with and without ESSN and in Table 4.9 are depicted the obtained results. The results show that with the utilization of accumulators, the total energy demanded by the system is reduced around a 7%.

The obtained results have been compared with the results given by the post-processing module of RailNeos. Those can be find in Fig. 4-18 and 4-19. These figures show the net energy balance of the system with and without ESSN respectively and it can be seen the energy demand reduction (≈ 7%) from the AC grid (right-bottom

Heavy traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[194.64, 254.81, 170.72]	kWh
Normal Operation with off-board accumulators	[179.03, 242.53, 155.58]	kWh
Average energy demand reduction	**7.24**	**%**

Table 4.9: Energy demand for the case of heavy traffic with and without ESSN.

side), as well as that the burned energy is much more lower in the case of using ESSN ($\approx 83\%$).

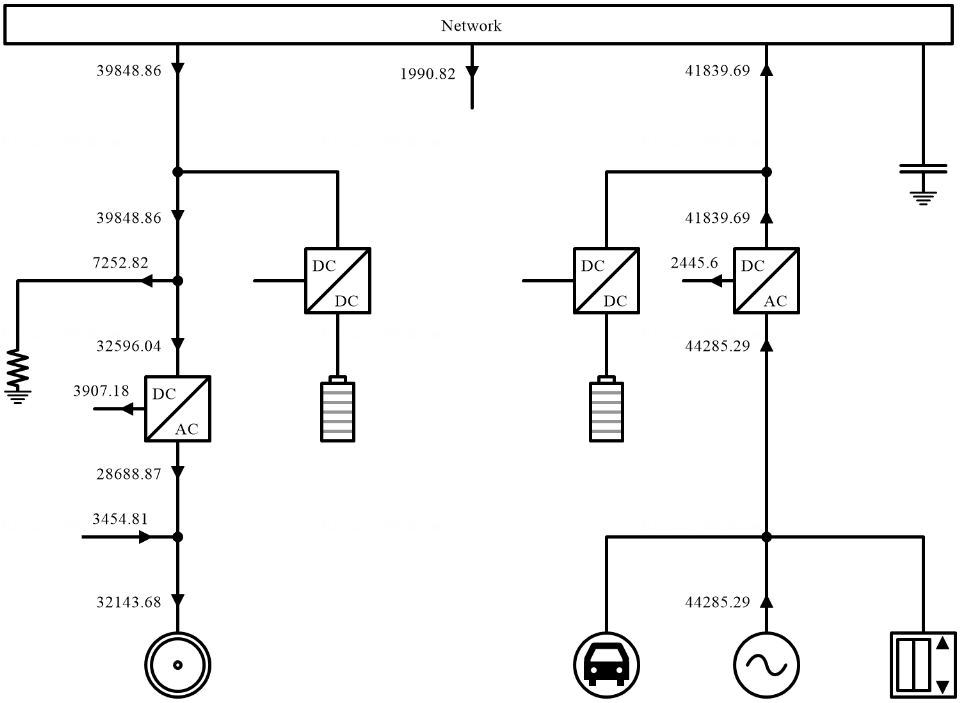


Figure 4-18: Net aggregated energy for the base case with non-reversible substations and no accumulators.

Finally, the annual bill have been computed for that new scenario, which has allowed to reduce the contracted power from [950, 1300, 900] kW to [900, 1200, 800] kW. Always taking into account a 15-20% upper margin over the maximum average power registered. Similarly, the new energy term has been calculated. In Fig. 4-20 is depicted the annual bill comparison of the system with and without ESSN. In conclusion, the bill is reduced in around a 7% if accumulators at substation level are used.

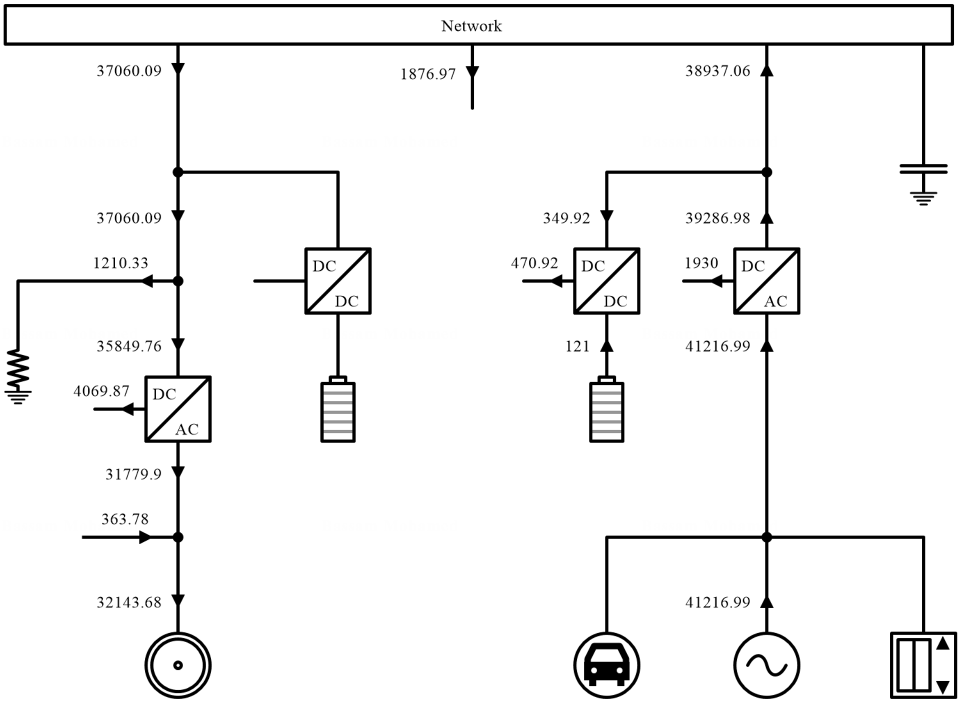


Figure 4-19: Net aggregated energy for the case with non-reversible substations and ESSN on the feeding substations.

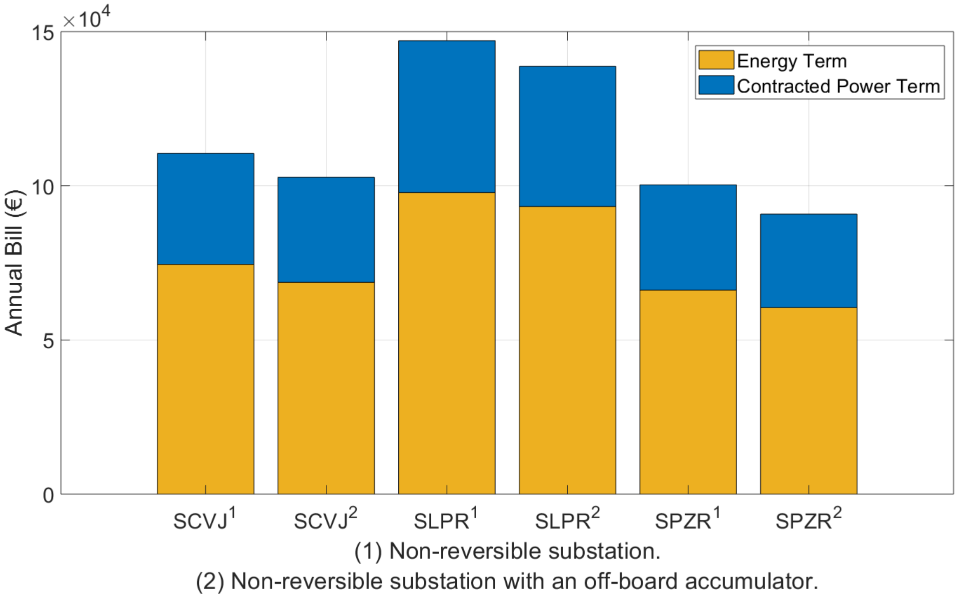


Figure 4-20: Annual bill comparison for the case of heavy traffic with and without ESSN.

On-board energy storage systems (ESST)

Secondly, it has been followed the same process, but with on-board batteries on the trains (which characteristics are described as the beginning of the present section).

The conclusions obtained are quite similar to ones done for the case of adding off-board accumulators. However, here it has been found an important distinction: the average power profile obtained slightly depends on the initial SOC of the batteries. In Fig. 4-21) it can be seen that the average power profile is lower in all the substations when comparing the case of having an initial SOC of 0% respect to the 100%.

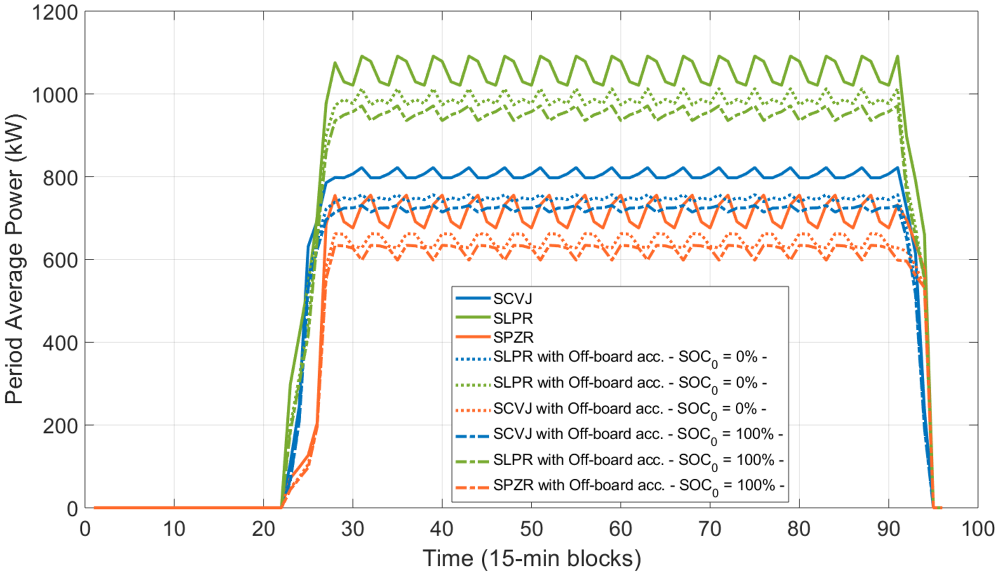


Figure 4-21: Period average power (15-min blocks) registered by the maximeter comparison for th case of heavy traffic with and without ESST.

This difference depending the initial SOC will foreseeably affect both the maximum power peak registered and the demanded energy by the system, being the reductions more significant in the case of starting the operation with the batteries fully charged. These results are depicted in Tables 4.8 and 4.9.

Additionally, in Fig .4-22 it is again shown the net energy balance obtained with the post-processing module of RailNeos for the case of adding ESST in order to validate the obtained conclusions. In this case, it can be seen the energy demand reduction (≈ 11%) from the AC grid (right-bottom side), as well as that the burned

Heavy traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[822.1, 1091.3, 755.5]	kW
Normal Operation with on-board accumulators ($SOC_0 = 0\%$)	[756.6, 1012.8, 662.5]	kW
Normal Operation with on-board accumulators ($SOC_0 = 100\%$)	[730.4, 971.3, 634.2]	kW
Average maximum power peak reduction ($SOC_0 = 0\%$)	**9.16**	%
Average maximum power peak reduction ($SOC_0 = 100\%$)	**12.74**	%

Table 4.10: Maximum registered averaged power by the maximeter for the case of heavy traffic with and without ESST.

Heavy traffic scenario	**[SCVJ, SLPR, SZPR]**	**Units**
Normal Operation	[194.64, 254.81, 170.72]	kWh
Normal Operation with on-board accumulators ($SOC_0 = 0\%$)	[180.04, 237.08, 154.2]	kWh
Normal Operation with on-board accumulators ($SOC_0 = 100\%$)	[174.24, 228.87, 148.86]	kWh
Average energy demand reduction ($SOC_0 = 0\%$)	**8.05**	%
Average Energy demand reduction ($SOC_0 = 100\%$)	**11.15**	%

Table 4.11: Energy demand for the case of heavy traffic with and without ESST.

energy is much more lower in the case of using ESSN ($\approx 87.5\%$).

Finally, the annual bill have been computed for the case of adding ESST with an initial SOC of the 0% and 100%. That new scenario has allowed to reduce the contracted power from [950, 1300, 900] kW to [800, 1200, 750] kW. Always taking into account a 15-20% upper margin over the maximum average power registered. Similarly, the new energy term has been calculated. In Fig. 4-23 it is depicted the annual bill comparison of the system with and without ESST (considering both the start of operation with the battery empty and fully charged). In conclusion, the bill is reduced in around a 7.8% when on-board with a $SOC_0 = 0\%$ are added and a 9.9% when on-board accumulators are added with a $SOC_0 = 100\%$.

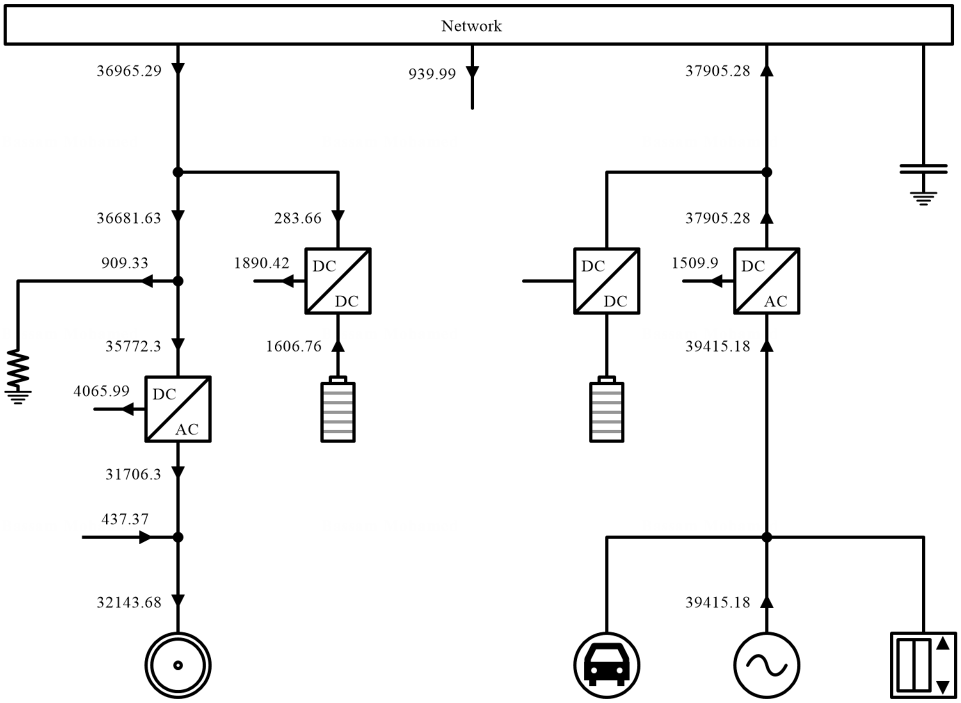


Figure 4-22: Net aggregated energy for the case with non-reversible substations and ESST.

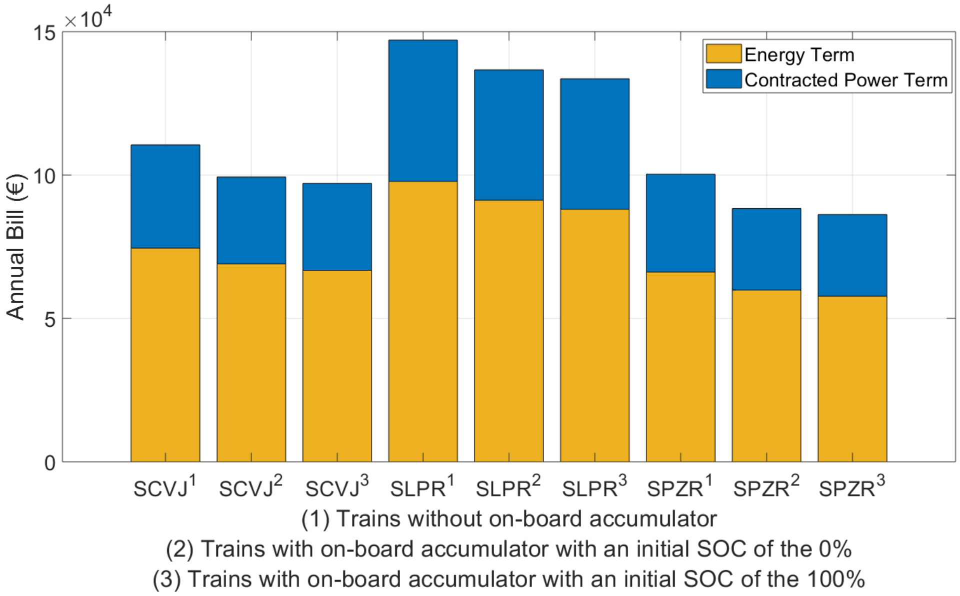


Figure 4-23: Annual bill comparison for the case of heavy traffic with and without ESST.

Chapter 5

Conclusion and Future Work

In this Master's Thesis, a tool to calculate the electricity bill based on the Spanish regulation has been implemented as a post-processing module of the railway simulation tool RailNeos. Furthermore, a methodology to optimally selected the required contracted power for railway systems has been proposed.

A detailed explanation of the software code has been presented as well as a verification of the same.

Following, the case study of Malaga-Fuenguirola-Alora has been presented and analysed in order to develop the mentioned method.

After having evaluated several scenarios within which the most unfavourable cases have been taken into account, it can be concluded that:

1. As a first conclusion, it can be stated that the optimal power to contract is the maximum average power registered by the meter. That is the point from which power penalization are applied.

2. As a general rule, to select the contracted capacity of a system the degraded cases of the same (that are the cases in which a feeding substation suffers a failure and does not provide service) should not be considered. The extra cost of raising the contracted power for these situations is much greater than the occasional penalties that may be caused. Nonetheless, a method to calculate the hours per year that it would compensate to have the system in failure before

it will compensate to increase the contracted power is presented.

3. The impact of heavy traffics on the correct selection of the contracted power will fully depend on the time period (time of the day and month of year) that this occurs. Therefore, to performed an analysis of the different traffic profiles is the clue to properly select the contracted power.

4. The utilization of track-side and on-board batteries helps to smooth the power peaks that later determine the optimal capacity to contract. Not only the contracted power term is reduced, but the energy term can be considerably lowered ($\approx 5 - 15\%$). Therefore, it is concluded that the use of accumulators help to minimize the electricity bill.

From the present work clear conclusion of a techno-economical analysis of DC railway systems are obtained. However, the work is developed for a singular case of study and it is independently implemented of the company's simulator. In a future, it will be essential to develop the method as a post-processing module of the simulator in order to get automatic analysis and conclusions. Moreover, to analyse mixed traffic profiles within a day should be something to consider. Finally, it will be of interest to evaluate the tariff regulation of other countries with which the company has projects in order to check the possibility of adapting the tool with minor changes and, therefore, get a optimal and personalised solution for each network.

Appendix A

Code of the Economic Module

A.1 Input data function: DCTS_Input_Data.m

```

function [Ptot, MatrixPeriods3X, MatrixPeriods6X, MatrixPricesTPA, MatrixPricesTEA, Node_ID, Mode, Pcontract, DaysPerMonth3x, DaysPerMonth6x] = DCTS_Input_Data(case_name, Pcontracted)

%---------Data--------------------------------------------
        path = pwd;
        folder_name = strcat('\','MLG_FGL_ALR_final','\',case_name,'\'); %type here the name of the foder in which the data base reults are saved
%---------Data from Data----------------------------------
        db_FileName = strcat(path,folder_name,'res.db');
        db = sqlite(db_FileName); % open the results database
        if (db < 0)
                error('Can not open the result database');
        end
%--------------------------------------------------------
        sql = sprintf(['SELECT Cfg.Start_Time, Cfg.Sim_Time FROM Cfg']);
        TmpMat = cell2mat(fetch(db, sql));
```

```
        StartTime = TmpMat(1) + 1; %in sec % The start time of the calculation
        EndTime =  StartTime + TmpMat(2) - 1; %in sec % The end time of the calculation
%--------------------------------------------------------
        sql = sprintf(['SELECT Node.ID, Base.Mode, Base.P1, Base.P2, Base.P3, Base.P4, Base.P5, Base.P6 FROM Base, Node WHERE Base.ID == Node.Base AND Node.Type !=0']);
        TmpMat = fetch(db, sql);
        Node_ID = double(cell2mat(TmpMat(:,1)));
        NodeNum = length(Node_ID);
        Mode = double(cell2mat(TmpMat(:,2)));
        %Pcontract = cell2mat(TmpMat(:,[3,4,5,6,7,8]))';
% Create SQL query to read the total power of the selected substation
        P = zeros(EndTime-StartTime + 1, NodeNum);
        for k = 1 : NodeNum
                Node = Node_ID(k);
                sql = sprintf(['SELECT Stp.t, OUT_Node.Total_P FROM OUT_Node, Stp WHERE Stp.ID = ', 'OUT_Node.Stp AND OUT_Node.Node = %d AND Stp.t <= %f'], Node, EndTime-1);
                TmpMat = cell2mat(fetch(db, sql));
                P(:,k) = TmpMat(:, 2); %only data of the simulated period, NOT 24h by defect
                % Total power (kW) -ve demand (AC to DC), +ve regeneration (DC to AC)
        end
        %t = TmpMat(:, 1); % Time vector (s)

        Ptot  = zeros(24*3600, NodeNum); %'Organize' P in the 24h vector (86400 instants)
        for k = 1 : NodeNum
                for Index = StartTime : EndTime
                        Ptot(Index,k) = P(Index - StartTime + 1,k);
                end
```

```
        end

%--------TARIFFS TABLES: PRICES and TIME DISCRIMINATION--------
        MatrixPeriods3X = dlmread(strcat(path,folder_name,'/COST/Timing_1.csv'), ',', 2, 1);  % define periods for 3X rates
        MatrixPeriods6X = dlmread(strcat(path,folder_name,'/COST/Timing_2.csv'), ',', 2, 1);  % define periods for 6X rates
        MatrixPricesTPA = dlmread(strcat(path,folder_name,'/COST/Price_P.csv'), ',', 1, 1);   % price for POWER TERM
        MatrixPricesTEA = dlmread(strcat(path,folder_name,'/COST/Price_E.csv'), ',', 1, 1);   % price for ENERGY TERM

%--------Select the initial TIME/DATE of the simulation-------
        % Number of days per month
        Matrix3X = dlmread(strcat(path,folder_name,'/COST/Timing_1.csv'), ',', 1, 1);  % define periods for 3X rates
        Matrix6X = dlmread(strcat(path,folder_name,'/COST/Timing_2.csv'), ',', 1, 1);  % define periods for 6X rates
        DaysPerMonth3x = Matrix3X(1,1:end-3);  %[31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31];
        DaysPerMonth6x = Matrix6X(1,1:end-1);  %[22, 19, 22, 21, 21, 11, 10, 22, 22, 21, 22, 21, 20, 111];
        %DaysPerMonth6x = DaysPerMonth6xPartial;
%---------------------------------------------------
        close(db);                      %close the database
end
```

A.2 Data reformatting function: DCTS_PT.m

```

function [Period_Pavg, Hour_Pavg, Hour_Pmax] = DCTS_PT(Ptot)

%----Select Simulation Sampling---------
```

```
        SamplePerSecond = 1;            % one sample per each second (for all simulation)
        SecondPerPeriod = 15 * 60;      % number of seconds in 15 minutes
        SamplePerPeriod = SamplePerSecond * SecondPerPeriod; % number of samples in a single period = 900
        SamplePerHour   = SamplePerSecond * 3600; % number of samples in a single hour
        PeriodPerHour   = SamplePerHour/SamplePerPeriod;

%%------------------------------------------------------
        k = Ptot > 0; % Find the index of samples where power flows from DC to AC
        Ptot(k) = 0;  % Assume no power flow from DC to AC
        Ptot = Ptot * (-1); % Get the positive value of the demand power
%-------------------------------------------------------
        NodeNum = size(Ptot,2);
        Period_Count    = ceil(length(Ptot) / SamplePerPeriod); % The count of full period in a simulation time
        Period_Pavg             = zeros(Period_Count , 1);                % The average  power in each 15 minutes

        for n = 1 : NodeNum
                SampleIndex     = 1 : SamplePerPeriod;  % The samples range of the first periods (1:900)
                for k = 1 : Period_Count
                        Period_Pavg(k,n) = mean(Ptot(SampleIndex,n));
                        SampleIndex = SampleIndex + SamplePerPeriod;  % Update the sample index to the next period
                end
        end
%   ------------------------------------------------------------------------
```

```
        Hour_Count       = 24;    % The count of 1 hour in a simulation time
        Hour_Pavg        = zeros(Hour_Count, NodeNum);    % The average  power in each hour
        Hour_Pmax        = zeros(Hour_Count, NodeNum);    % The maximum power in each hour

        for n = 1 : NodeNum
                for k = 1 : Hour_Count
                        IndexFirstMeasure = (k - 1) * PeriodPerHour + 1;
                        IndexLastMeasure  = IndexFirstMeasure + PeriodPerHour - 1;
                        Hour_Pavg(k,n)    = mean(Period_Pavg(IndexFirstMeasure: IndexLastMeasure, n));
                        Hour_Pmax(k,n)    = max(Period_Pavg(IndexFirstMeasure: IndexLastMeasure, n));
                end
        end
end
```

A.3 3-rates bill calculation: DCTS_Bill_3x.m

```
function [TotalBillPerPeriod, BillPerYear] = DCTS_Bill_3x(Period_Pavg, Hour_Pavg, Hour_Pmax, MatrixPeriods3X, MatrixPricesTPA, MatrixPricesTEA, Mode, Pcontract, DaysPerMonth3x)

%% --- BOE Parameters-----------------------------
        K3x = 0.1;
        LowParameter3x  = 0.85;
        HighParameter3x = 1.05;
        Periods    = [1 2 3];

```

```
%% --------POWER PENALTY CALCULATION TARIFFs 3.X--------------
        MaxPowerPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods3X,2) - 3);
        for month=1:12
                for k = Periods %1:3
                        PeriodIndex = ismember(MatrixPeriods3X(:,month), k);
                        if (sum(PeriodIndex) >= 1) %(24x12)
                                MaxPowerPerPeriodPerMonth(k, month) = max(Hour_Pmax(PeriodIndex));
                        end
                end
        end

% At that point it is necessary to check if the maximum measures exceed
% the contracted power values, in order to obtain the MODIFIED POWERS that will be the ones used to calculate the bill.

        MaxPowerPerPeriodPerMonthModified = MaxPowerPerPeriodPerMonth;
        for n = 1 : size(MaxPowerPerPeriodPerMonthModified, 2)
                for r = 1 : size(MaxPowerPerPeriodPerMonthModified, 1)
                        %If the Consumed Power is less than the 85% of the contrated power, that is the power considered to compute the bill
                        if (MaxPowerPerPeriodPerMonthModified(r,n) < LowParameter3x * Pcontract(r))
                                MaxPowerPerPeriodPerMonthModified(r,n) = LowParameter3x * Pcontract(r);
                        %If the Consumed Power is between the 85% and 105% of the contrated power, the power considered to compute the bill is the contrated power
```

```matlab
                        elseif (((LowParameter3x * Pcontract(r)) <= MaxPowerPerPeriodPerMonthModified(r,n)) && MaxPowerPerPeriodPerMonthModified(r,n) <= (HighParameter3x * Pcontract(r)))
                                MaxPowerPerPeriodPerMonthModified(r,n) = Pcontract(r);
                        %If the Consumed Power is higher than the 105% of the contrated power, a penalization is applied: Pdi = PMdi + 2 * (PMdi - 1.05*PMi)
                        elseif (MaxPowerPerPeriodPerMonthModified(r,n) > HighParameter3x * Pcontract(r))
                                MaxPowerPerPeriodPerMonthModified(r,n) = MaxPowerPerPeriodPerMonthModified(r,n) + 2 * (MaxPowerPerPeriodPerMonthModified(r,n) - HighParameter3x * Pcontract(r));
                        end
                end
        end

%% -----------------POWER TERM BILL --------------------------------------
        PricekWPerPeriodPerDay = MatrixPricesTPA(:,Mode)/sum(DaysPerMonth3x); % price per day [eur/kW*day]
        PowerBillPerPeriodPerMonth = zeros(size(MaxPowerPerPeriodPerMonthModified,1)+1, size(MaxPowerPerPeriodPerMonthModified,2));
        for n = 1 : size(MaxPowerPerPeriodPerMonthModified, 2)
                for r = 1 : size(MaxPowerPerPeriodPerMonthModified,1)
                        PowerBillPerPeriodPerMonth(r,n) = MaxPowerPerPeriodPerMonthModified(r,n) * DaysPerMonth3x(n) *
```

```
                                PricekWPerPeriodPerDay(r);
                end
        end
        PowerBillPerPeriodPerMonth(length(Periods)+1,:) = sum(PowerBillPerPeriodPerMonth);
        PowerBillPerPeriodPerYear = sum(PowerBillPerPeriodPerMonth(length(Periods)+1,:));

%% -----------------ENERGY TERM BILL ------------------------------------
        AvgEnergyPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods3X, 2)-3); %3x12
        PricekWhPerPeriodPerDay = MatrixPricesTEA(:, Mode); % price per day [eur/kWh]
        EnergyBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods3X, 2) - 3); %4x12

        for month = 1 : size(AvgEnergyPerPeriodPerMonth, 2) %1:12
                for k = Periods %1:3
                        [row]=find(ismember(MatrixPeriods3X(:, month), k));
                        for idx = row'
                                AvgEnergyPerPeriodPerMonth(k, month) = Hour_Pavg(idx) + AvgEnergyPerPeriodPerMonth(k, month);
                        end
                        EnergyBillPerPeriodPerMonth(k, month) = AvgEnergyPerPeriodPerMonth(k, month) * DaysPerMonth3x(month) * PricekWhPerPeriodPerDay(k);
                end
        end
        EnergyBillPerPeriodPerMonth(end,:) = sum(EnergyBillPerPeriodPerMonth);

```

```
%% -----------------TOTAL BILL ---------------------------------------------
        TotalBillPerPeriod = zeros(size(MaxPowerPerPeriodPerMonthModified,1)+1, size(MaxPowerPerPeriodPerMonthModified,2));
        for n = 1 : size(MaxPowerPerPeriodPerMonthModified, 2)
                for r = 1 : size(MaxPowerPerPeriodPerMonthModified,1)
                        TotalBillPerPeriod(r,n) = PowerBillPerPeriodPerMonth(r,n) + EnergyBillPerPeriodPerMonth(r,n);
                end
        end
        TotalBillPerPeriod(length(Periods)+1,:) = sum(TotalBillPerPeriod);
        BillPerYear = sum(TotalBillPerPeriod(length(Periods)+1,:));
end
```

A.4 6-rates bill calculation: DCTS_Bill_6x.m

```
function [ContractedPowerBillPerPeriodPerMonth, PenalizationPerPeriodPerMonth, EnergyBillPerPeriodPerMonth, TotalBillPerPeriod, BillPerYear] = DCTS_Bill_6x(Period_Pavg, Hour_Pavg, MatrixPeriods6X, MatrixPricesTPA, MatrixPricesTEA, Mode, Pcontract, DaysPerMonth6x)

%% --- BOE Parameters-------------------------
XFactor6x = 1.4064;
K6x = [1 0.5 0.37 0.37 0.37 0.17];
Periods   = [1 2 3 4 5 6];

%% -----------POWER TERM CALCULATION TARIFFs 6.X----------------

%--------FIX POWER TERM DEPENDING ON THE CONTRACTED POWER-------
        PricekWPerPeriodPerDay = MatrixPricesTPA(:,Mode)/365;
```

```
        ContractedPowerBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X,2)-1); %7:14
        for month = 1 : size(MatrixPeriods6X,2) - 1  %1:14
                for k = Periods %1:6
                        ContractedPowerBillPerPeriodPerMonth(k,month) = Pcontract(k) * DaysPerMonth6x(month) * PricekWPerPeriodPerDay(k);
                end
        end
        ContractedPowerBillPerPeriodPerMonth(end,:) = sum(ContractedPowerBillPerPeriodPerMonth);
        ContractedPowerBill = sum(ContractedPowerBillPerPeriodPerMonth(end,:));

%-------BIL POWER TERM DEPENDING ON THE EXCESS: PENALTY -----------
        ContractedPowerPerPeriodPerMonth = zeros(length(Periods),size(MatrixPeriods6X,2)-1); %6x14
        for month = 1 : size(MatrixPeriods6X,2) %1:14
                for k = Periods %1:6
                        if (sum(ismember(MatrixPeriods6X(:, month),k)) > 0) %(24x14)
                                ContractedPowerPerPeriodPerMonth(k,month) = Pcontract(k);
                        end
                end
        end
        PowerPerPeriod = zeros(length(Period_Pavg), size(MatrixPeriods6X, 2)-1); %96x14
        Aei = zeros(length(Periods), size(MatrixPeriods6X, 2)-1); %6x14
        for month = 1 : size(MatrixPeriods6X,2) - 1  %1:14
                for k = 1 : length(Period_Pavg) %1:96
                        h = ceil(k/4);
                        period_idx = MatrixPeriods6X(h, month);
                        PowerPerPeriod(k, month) = ContractedPowerPerPeriodPerMonth(
```

```
                    period_idx, month);
            if(Period_Pavg(k) > PowerPerPeriod(k, month))
                Aei(period_idx, month) = Aei(period_idx, month) + DaysPerMonth6x(month) * (Period_Pavg(k) - PowerPerPeriod(k, month))^2;
            end
        end
        Aei(:,month) = sqrt(Aei(:,month));
    end

    FEP = zeros(length(Periods), size(MatrixPeriods6X, 2)-1); %6x14
    PenalizationPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X, 2)-1); %7x14
    for month = 1 : size(MatrixPeriods6X,2) - 1 %1:14
        for k = Periods %1:6
            FEP(k, month) = K6x(k) * XFactor6x * Aei(k, month); %6x14
            PenalizationPerPeriodPerMonth(k, month) = PenalizationPerPeriodPerMonth(k, month) + FEP(k, month); %7x14
        end
    end
    PenalizationPerPeriodPerMonth(end,:) = sum(PenalizationPerPeriodPerMonth);
    PowerPenalizationBill = sum(PenalizationPerPeriodPerMonth(end,:));
% -----------------POWER TERM BILL --------------------------------------
    PowerBillPerPeriodPerMonth(:,:) = ContractedPowerBillPerPeriodPerMonth + PenalizationPerPeriodPerMonth(:,:);
```

```
        PowerBillPerPeriodPerYear = sum(PowerBillPerPeriodPerMonth(length(Periods)+1,:));

%% -----------------ENERGY TERM BILL --------------------------------------
        AvgEnergyPerPeriodPerMonth = zeros(length(Periods), size(MatrixPeriods6X, 2) - 1); %6x14
        PricekWhPerPeriodPerDay = MatrixPricesTEA(:, Mode); % price per day [eur/kWh]
        EnergyBillPerPeriodPerMonth = zeros(length(Periods)+1, size(MatrixPeriods6X, 2) - 1); %7x14

        for month = 1 : size(MatrixPeriods6X, 2) - 1 %1:14
                for k = Periods %1:6
                        [row] = find(ismember(MatrixPeriods6X(:, month), k));
                        for idx = row'
                                AvgEnergyPerPeriodPerMonth(k, month) = Hour_Pavg(idx) + AvgEnergyPerPeriodPerMonth(k, month);
                        end
                        EnergyBillPerPeriodPerMonth(k, month) = AvgEnergyPerPeriodPerMonth(k, month) * DaysPerMonth6x(month) * PricekWhPerPeriodPerDay(k);
                end
        end
        EnergyBillPerPeriodPerMonth(end,:) = sum(EnergyBillPerPeriodPerMonth);

%% -----------------TOTAL BILL--------------------------------------

        TotalBillPerPeriod = zeros(length(Periods)+1, size(MatrixPeriods6X, 2) - 1); %7x14
        for month = 1 : size(MatrixPeriods6X, 2) - 1 %1:14
```

```
                for k = Periods %1:7
                        TotalBillPerPeriod(k, month) = PowerBillPerPeriodPerMonth(k, month) + EnergyBillPerPeriodPerMonth(k, month);
                end
        end
        TotalBillPerPeriod(end,:) = sum(TotalBillPerPeriod);
        BillPerYear = sum(TotalBillPerPeriod(end,:));
end
```

A.5 Get results: Results.m

```
function  [ContractedPowerBill, Penalization, EnergyBill, TotalBill, BillPerPeriod6x, BillPerPeriod3x, Period_Pavg]=Results(case_name, Pcontracted)

%----Call Input Data Function ---------------------------------------------
        [Ptot, MatrixPeriods3X, MatrixPeriods6X, MatrixPricesTPA,...
        MatrixPricesTEA, Node_ID, Mode, Pcontract, DaysPerMonth3x, DaysPerMonth6x] = DCTS_Input_Data(case_name, Pcontracted);

%------Call the function which calculated the maximum and average power
%per period and per hour ------------------------------------------------
        [Period_Pavg, Hour_Pavg, Hour_Pmax] = DCTS_PT(Ptot);

        %Initialize variables that you later want as output
        BillPerPeriod3x = zeros(4,12,length(Node_ID));
        BillPerPeriod6x = zeros(7,14,length(Node_ID));
        ContractedPowerBill = zeros(1,length(Node_ID));
        Penalization = zeros(1,length(Node_ID));
        EnergyBill = zeros(1,length(Node_ID));
```

```
    TotalBill = [];
    for node = 1 : length(Node_ID) %loop over all the nodes (feeding substations)
        ModePerNode = Mode(node); %take mode of the actual node
        Period_Pavg_PerNode = Period_Pavg(:,node); %take average power per period of the actual node
        Hour_Pavg_PerNode = Hour_Pavg(:,node); %take average power per hour of the actual node
        Hour_Pmax_PerNode = Hour_Pmax(:,node); %take maximum power per hour of the actual node
        PcontractPerNode = Pcontract(:,node); %take the contracted power in each period of the actual node
        %Call 3-rate function calculation if mode is 1 or 2 (3.0 and 3.1 rates)
        if (ModePerNode <= 2)
            [TotalBillPerPeriod, BillPerYear] = DCTS_Bill_3x(Period_Pavg_PerNode, Hour_Pavg_PerNode, Hour_Pmax_PerNode,...
            MatrixPeriods3X, MatrixPricesTPA, MatrixPricesTEA, ModePerNode, PcontractPerNode, DaysPerMonth3x);
            BillPerPeriod3x(:,:,node)  = TotalBillPerPeriod; %save total bill in a matrix month by month
        %Call 6-rate function calculation if mode is 3 or greater (6.1 to 6.5 rates)
        elseif (ModePerNode > 2)
            [ContractedPowerBillPerPeriodPerMonth, PenalizationPerPeriodPerMonth, EnergyBillPerPeriodPerMonth, TotalBillPerPeriod, BillPerYear] = DCTS_Bill_6x(Period_Pavg_PerNode, Hour_Pavg_PerNode, MatrixPeriods6X, MatrixPricesTPA, MatrixPricesTEA,
```

```
                                ModePerNode, PcontractPerNode, DaysPerMonth6x);
                        ContractedPowerBill(node) = sum(ContractedPowerBillPerPeriodPerMonth(end,:));
                        Penalization(node) = sum(PenalizationPerPeriodPerMonth(end,:));
                        EnergyBill(node) = sum(EnergyBillPerPeriodPerMonth(end,:));
                        BillPerPeriod6x(:,:,node) = TotalBillPerPeriod; %save total bill in a matrix month by month
                end
                TotalBill = [TotalBill , BillPerYear];
        end
end
```

A.6 Contracted power optimization with 'fmincon'

```
function [SOL]=Optimization()

        % Pcontracted = ones(6,3); %USE IT IF YOU WANT A DIFFERENT CONTRACTED POWER THAT THE ONE SPECIFIED IN RAILNEOS
        Pcontracted(:,1) = ones(6,1).*500;
        Pcontracted(:,2) = ones(6,1).*600;
        Pcontracted(:,3) = ones(6,1).*500;
        X0 = Pcontracted;

%----Call Input Data Function---------------------------------------------
        [Ptot, MatrixPeriods3X, MatrixPeriods6X, MatrixPricesTPA,...
        MatrixPricesTEA, Node_ID, Mode, Pcontract, DaysPerMonth3x, DaysPerMonth6x] = DCTS_Input_Data("MLG-FGL-ALR_L1_0", Pcontracted);

```

```
%------Call the function which calculated the maximum and average power per period and per hour------------------------------------------------
        [Period_Pavg, Hour_Pavg, Hour_Pmax] = DCTS_PT(Ptot);

%Solve the OPF problem
        A=[]; Aeq=[]; b=[]; beq=[]; lb=[]; ub=[];
        options=optimset('Display','Iter');
        [SOL,fval,exitflag,output,lambda,grad,hessian]=fmincon(@myfun,X0,A,b,Aeq,beq,lb,ub,@mycon,options);

        function [c ceq]=mycon(X)
                Pcontracted = X;
                c = zeros((size(Pcontracted,1)-1)*size(Pcontracted,2),1); %inecuaciones
                idx = 1;
                for n = 1:size(Pcontracted,2)
                        for k = 1:size(Pcontracted,1)-1
                                c(idx) = Pcontracted(k,n)-Pcontracted(k+1,n);
                                idx = idx + 1;
                                c(idx) = 100-Pcontracted(k,n);
                                idx = idx + 1;
                        end
                        c (idx) = 100-Pcontracted(k,n);
                        idx = idx + 1;
                end
                ceq = []; %ecuaciones
        end

        function F=myfun(X)
                Pcontract=X;
                BillPerPeriod3x = zeros(4,12,1);
                BillPerPeriod6x = zeros(7,14,1);
                ContractedPowerBill = zeros(1,length(Node_ID));
                Penalization = zeros(1,length(Node_ID));
```

```
        EnergyBill = zeros(1,length(Node_ID));
        TotalBill = [];
        for k = 1 : length(Node_ID)
                ModePerNode = Mode(k);
                Period_Pavg_PerNode = Period_Pavg(:,k);
                Hour_Pavg_PerNode = Hour_Pavg(:,k);
                Hour_Pmax_PerNode = Hour_Pmax(:,k);
                PcontractPerNode = Pcontract(:,k);
                if (ModePerNode <= 2)
                        [TotalBillPerPeriod, BillPerYear] =
                           DCTS_Bill_3x(Period_Pavg_PerNode,
                            Hour_Pavg_PerNode,
                           Hour_Pmax_PerNode,MatrixPeriods3X
                           , MatrixPricesTPA,
                           MatrixPricesTEA, ModePerNode,
                           PcontractPerNode, DaysPerMonth3x)
                           ;
                        BillPerPeriod3x(:,:,k)  =
                           TotalBillPerPeriod;
                elseif (ModePerNode > 2)
                        [
                           ContractedPowerBillPerPeriodPerMonth
                           ,PenalizationPerPeriodPerMonth,
                           EnergyBillPerPeriodPerMonth,
                           TotalBillPerPeriod, BillPerYear]
                           = DCTS_Bill_6x(
                           Period_Pavg_PerNode,
                           Hour_Pavg_PerNode,
                           MatrixPeriods6X, MatrixPricesTPA,
                            MatrixPricesTEA, ModePerNode,
                           PcontractPerNode, DaysPerMonth6x)
                           ;
                        ContractedPowerBill(k) = sum(
                           ContractedPowerBillPerPeriodPerMonth
                           (end,:));
```

```
                Penalization(k) = sum(PenalizationPerPeriodPerMonth(end,:));
                EnergyBill(k) = sum(EnergyBillPerPeriodPerMonth(end,:));
                BillPerPeriod6x(:,:,k) = TotalBillPerPeriod;
            end
            TotalBill = [TotalBill , BillPerYear];
        end
        F = sum(TotalBill);
    end
end
```

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