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DC Traction system cost estimation tool taking into account losses minimization

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ABSTRACT

This dissertation proposes a tool that will give support to the design of DC traction systems. The tool simulates a simplified model, with three substations and the goal is to find the system configuration that minimizes the distribution system (catenary) losses.

The existing software tools allow to simulate power traction systems, although, it is usual to take long time to optimize them and carries difficulties to find optimal solutions.

The tool presented in this work, developed in a simulation software, allows modeling a system, where a vehicle operates in a line, fed by a traction supply system composed by three traction substations. It becomes possible to simulate the system, considering all the assumptions and simplifications, getting mechanical and electrical results. The methodology allows to size the traction groups, the section for parallel feeder cable and the length of each electrical section, using the best location for the intermediate substation.

A comparative study between two scenarios is proposed and it is presented a method to globally simulate the system, verifying the best configuration between the several hypothesis. Thus giving the best solution for the system in analysis.

Keywords: modelation, traction, energy, transportation, optimization, railways.

RESUMO

Esta dissertação propõe uma ferramenta que dará suporte aos estudos de tração alimentados a corrente contínua. O algoritmo desta ferramenta simula um modelo simplificado com três subestações e o objetivo é encontrar a configuração de sistema que minimiza as perdas no sistema de distribuição (catenária).

As ferramentas existentes permitem simular sistemas de tração de potência, apesar de, usualmente ser um processo demoroso e que apresenta dificuldades para encontrar soluções ótimas.

A ferramenta apresentada nesta dissertação, desenvolvida com um software de simulação, permite modelar um sistema, onde um veículo opera ao longo de um trecho de via, alimentado por três subestações de tração. Considerando todas as simplificações inerentes ao desenvolvimento, permite a possibilidade de simular o modelo, extraindo resultados mecânicos e elétricos da operação. A metodologia permite dimensionar os grupos retificadores das subestações, a secção do cabo paralelo de tração, bem como o comprimento das secções elétricas, através da posição ótima da subestação intermédia.

Um estudo comparativo entre dois cenários é proposto e é apresentado um método para globalmente simular o sistema, verificando a melhor configuração entre as várias hipóteses. Portanto, dando a melhor solução para o sistema em análise.

Palavras-chave: modelação, tração, energia, transportes, optimização, Simulink®, Matlab®.

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ACRONYMS

AC Direct Current.

D12 Distance between substations TPS1 and TPS2.

D23 Distance between substations TPS2 and TPS3.

DC Direct Current.

GA Genetic Algorithm.

LOC Substation TPS2 location code reference.

LRT Light Rail Transit.

PFC Section of Parallel Feeder Cable code reference.

PID Proportional-Integral-Derivative.

PK Point Kilometric.

RMS Root Mean Square.

ST Station.

TPS Traction Power Substation.

INTRODUCTION

1.1 Motivation

The current outlook of the world relatively the high consumption of fossil fuels and the warn of the decrease in the amount of reserves, becomes fundamental to optimize as most as possible the transportation railway systems and avoid losses.

This dissertation offers a complementary tool to study and understand a DC traction system.

The software tool of this dissertation offers not only a complementary tool to existing simulator tools, but also an opportunity to study and understand a DC traction system. The possibility of identifying possible optimal solutions for a traction system, in particular through an economic analysis of its operation is the main motivation for this dissertation.

This type of systems has many advantages, such being relatively eco-friendly, easier to handle, that allows easy speed control, high efficiency and low maintenance.

DC traction systems usually use light rails or trams, as their rolling stock, to operate the lines. As example, in figure 1.1 can be seen the tram operating in Dublin city [8]. To feed these vehicles a power supply system is used, which is the main scope of this dissertation. These systems are considered convenient, sustainable and environmentally friendly. Higher prices for energy resources and the growing number of passengers that are shifting away from private transport to public transportation shows that it is becoming increasingly important to optimize these systems [1].

2018 was a successful year for urban rail infrastructure, despite a 6% slowdown of growth pace. 121 urban rail projects were completed on all continents, totaling 1270 km, compared to 1348 km in the previous year. It is registered that, 75 individual metro infrastructures projects were completed in 39 cities, in a total of 960 km. For Light rail market,

it is registered that 46 single infrastructure projects were completed in 40 cities, in a total of 309 km [31]. These numbers are presented in figure 1.2.

This dissertation proposes the development of a methodology that allows to optimize a DC traction system, as to the position of the middle substation and the section for the parallel feeder cable.



Figure 1.1: Tram Citadis 401 in Bernburb Street of Dublin.

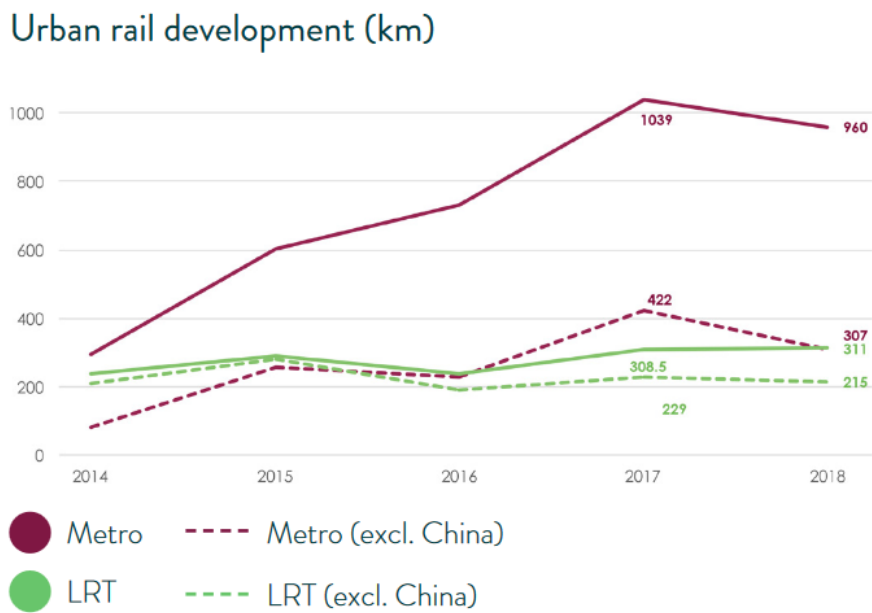


Figure 1.2: Urban Rail development in km for Metro and Light Rail Transportation rail (LRT) systems

1.2 Objectives

This dissertation will focus on an automated software tool that allows to estimate the minimum cost for a DC traction system (estimated energy supply system and losses costs). The first objective is to create an automated process that allows achieving the optimum system configuration. To find this optimum configuration, the process will have to simulate an operation condition and extract electromechanical results. In figure 1.3 is possible to see a scheme that shows a vehicle operating in a 750 Vdc traction system, which uses an energy distribution system and two common traction substations. The second objective is to identify and evaluate the situations where it is profitable to use a higher section for parallel feeder cable. Using a higher section will lead a decrease of losses in the catenary circuit, for the same operation conditions.

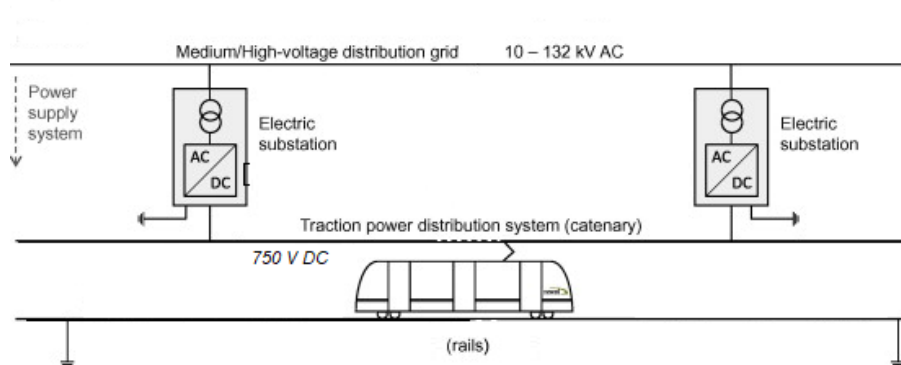


Figure 1.3: Vehicle operating in a 750Vdc traction system, adapted from [11].

In resume the thesis objectives are:

- Develop a DC traction system model that allows to simulate an operation with one vehicle and three substations and extract the respective electromechanical results.
- Develop a methodology to use the simulation results, from first point, and estimate the best system configuration taking into account losses minimization;
- Elaborate a comparative analysis that shows the system configuration impact on catenary losses.

1.3 Dissertation Structure

This dissertation is divided in five chapters. The first chapter is an introduction to the project, explaining and justifying the purpose of this dissertation and detailing the respective structure.

The second chapter introduces the main characteristics about DC traction systems using relevant published literature. Then is presented some railway simulator tools, describing their methodology and showing their features.

The electric traction system model and the calculation methods is shown in third chapter, including reference values for traction supply equipment.

In chapter four is showed the simulation results in order to analyses and evaluate the used calculation model. It is showed a comparative study between system configurations, evaluating the best configuration.

For last, in chapter five is presented the final conclusions of this dissertation and it is showed the suggestions for a future work.

STATE-OF-THE-ART

This chapter presents the conclusions from published research literature and present the most used railway simulator tools.

2.1 Introduction

This section shows some research that has been published in the recent years. To get a sustainable urban rail transportation, each detail has to be taken into account during the traction system design.

The DC traction power system is composed of the consumers, which is mainly the vehicles that operate in the track, and the power supply system, composed of: substations and the distribution system (catenary), as shown in figure 2.1.

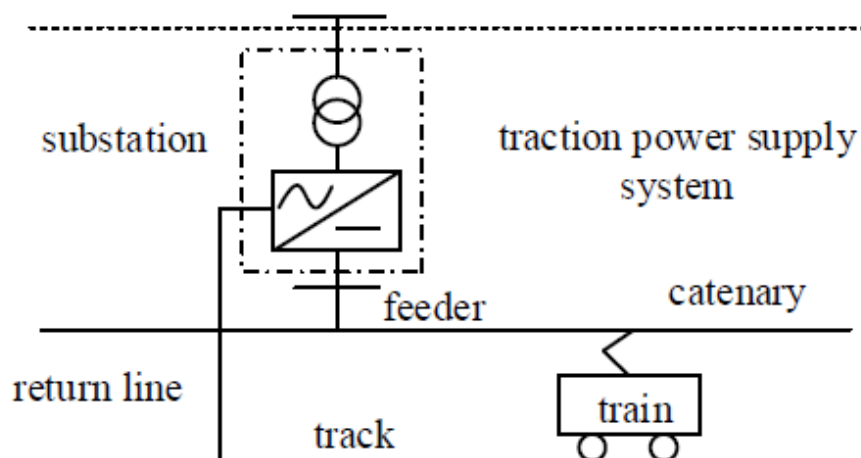


Figure 2.1: DC traction system general structure, adapted from [11].

In the DC traction system of urban rail transportation, substations are the facilities that provides the 750V or 1500V voltage for the vehicles to run and they are placed along the route spaced, usually, between one and three, for 750V and between three and six, for 1500V [11].

The traction distribution system is mainly composed of the catenary circuit and rails circuit. The catenary system is composed of a contact wire and usually by a parallel feeder cable, that allows for provide a higher current flow to feed the vehicles. The conductor material, are usually copper or aluminum. Figure 2.2 shows a catenary and rails systems.

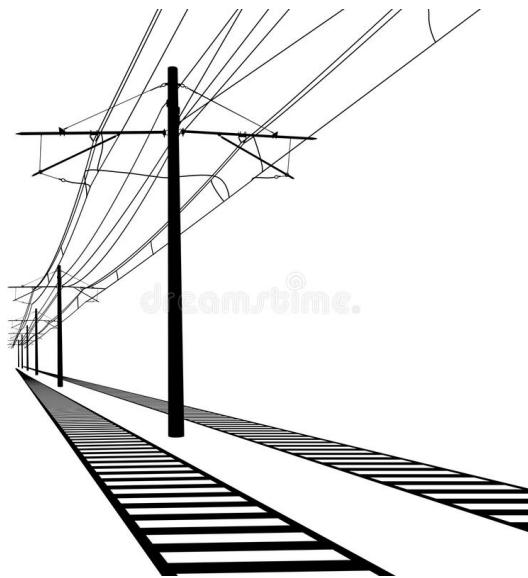


Figure 2.2: Overhead contact system and rails circuit

2.1.1 Physical parameters of a system

Physical parameters that influence the traction system performance have been explored and are presented below. The performance are evaluated by the operation efficiency, considering mainly by the trip time and the consumption.

- **Operation schedule and timetable.** These parameters define the exploration capacity of the line;
- **Track gradient.** Positive and negative slopes of the track;
- **Vehicle mass.** Representing the vehicle tare plus the respective capacity during an operation;
- **Limitation on acceleration and deceleration values.** Fundamental parameter from vehicle kinematics, that might influence directly the operation consumption.

- **Regenerative braking.** It is an energy recovery mechanism that allows the vehicles that are braking to generate electricity back to distribution system and being used by other vehicles, saving energy from the power source;
- **Traction Power Substations locations.**

To show the importance of these parameters it was explored a report made in 2016, where some simulation results was achieved using real data from Beijing Yizhuang line, which belongs to Beijing metro system, in China. The line has around 23 km of railway. It started operating in 2010 and it has 14 stations, including six underground, to ensure the daily transportation of 173.5 thousand passengers in average, values from 2014 [6] [30].



Figure 2.3: Yizhuang line map from Beijing metro system, from [6].

According to this study, the possible factors that influence the traction energy consumption are the trip time, the track gradient, the running resistance, the maximum traction and braking forces, the regenerative braking and the train mass, as can be seen as follow [29].

2.1.1.1 Operation schedule and timetable

Increasing the trip time, the energy consumption decreases. As an example is showed that the consumption increases by 3.4 kWh when the trip time is reduced from 160 to 150 seconds, compared to 4.8 kWh when the trip time is reduced from 150 to 140 seconds. So, two techniques can be applied, as can be seen below:

- Increase the trip time by reducing the time where the train is stopped;
- Timetable optimization.

A timetable from a public transport service is a document that shows the information of the schedules during specific hours of the day, it allows to assist passengers with a planning trip.

It can be represented as a Position/Time graphic that shows the vehicles trajectory during the time trip, as can be seen in figure 2.4.

The main purpose to use timetables information in simulation designs are to achieve the best possible exploration capacity by using the railway infrastructure [21].

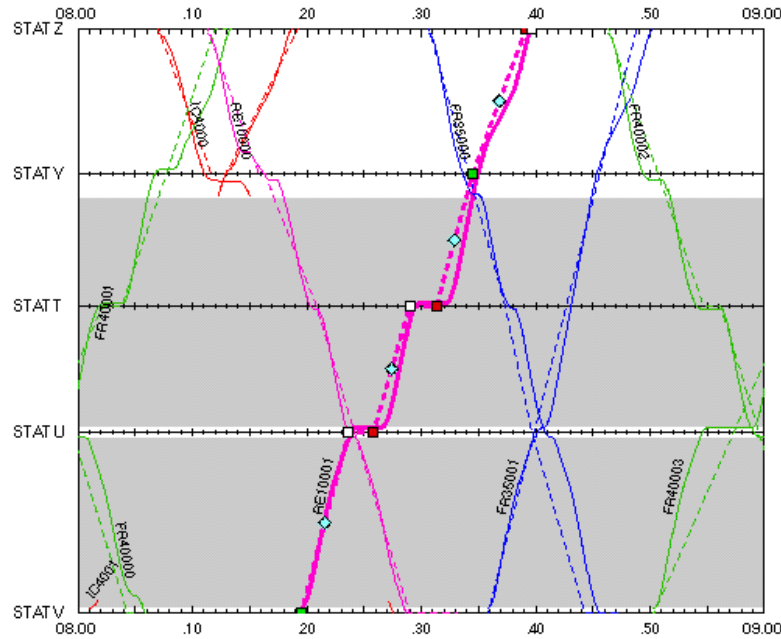


Figure 2.4: Timetable graphic representation, adapted from [20].

Other authors developed techniques to optimize the timetable: Lin Chen, suggests to apply genetic algorithms to optimize train scheduling. The main idea is to avoid the simultaneous acceleration from many trains, in order to reduce the maximum traction power [5].

2.1.2 Track gradient

In the region where the vehicle climbs up the consumption tends to increase, which increases the voltage drop on contact line, from the supply network distribution. This impact was studied by Nguyen Viet [19]. In figure 2.5, it is possible to see the referred situation representation.

The authors from [29], also studied the track gradient impact on the vehicle's energy consumption. Psychically, it occurs because more traction force must be applied to deliver the required trip time for a steeper uphill climb. The results shows that the consumption increases 0.8 kWh when the gradient of the starting section gains 0.2% uphill, compared to only 0.1 kWh for the middle and caudal sections [29].

An interesting qualitative conclusion is that the gradient in the middle section has

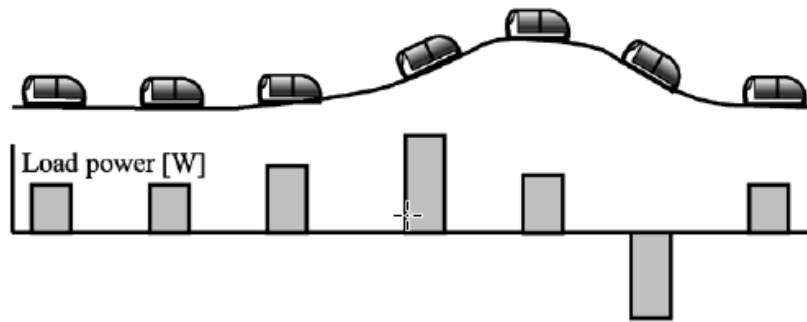


Figure 2.5: Load Power along a sloping route

little influence on the total traction energy consumption of the operational systems, although the slopes near stations could contribute to saving energy. For trains running in the middle section, the downhill slope could help the trains achieve a high speed in a shorter time [29]. For these reasons, important measures of the energy-efficient gradient design are concluded as follows.

- Increase the gradient near stations;
- Proper length of the gradient.

2.1.3 Train Mass

The influence of the train mass on the traction energy consumption was studied in [29]. To see this influence, the running time has being fixed. It was cleared verified that the heavier the train is, more energy it will be used during the trip. The results show that the energy consumption is nearly doubled when the train mass increases by 50%. Hence, a mass reduction is proposed as one of the important strategies to save energy, mainly by developing vehicle structures with lighter materials, such as aluminum or alloy [29] [4].

2.1.4 Maximum Acceleration and Braking

The acceleration and braking maximum values are usually choose by the estimated passenger comfort level. However, this value might affect hugely the operation consumption [21].

Typically these values are between 0.02 and 1 m/s^2 for heavy trains and 1 and 3 m/s^2 for metro and light transportation systems.

The results reveal that the consumption has a gentle decrease with the increase of the maximum traction and braking forces. Numerically, these consumptions are 23.9 , 23.5 , 22.5 and 21.9 kWh , with the corresponding maximum braking forces 255 , 270 , 305 and 345 kN . Comparing with two different speed profiles, it was discovered that the train with a higher braking rate can come to a stop more quickly, and therefore a lower speed is needed to perform the operation and complete the route, which could reduce the global

consumption in the operation. In conclusion, vehicles with larger limitation to traction and braking forces are more efficient [29].

2.1.5 Regenerative braking

An efficient use of the regenerative energy could make a great difference in reducing the energy consumption in systems. The energy is fed back to the power network, such that it can be used by other accelerating trains. The energy could also be stored in storage systems and be reused by trains later.

For the storage of the regenerative energy, batteries, super-capacitors or fly wheels, should be installed. These storage systems can be divided into two types, on the trains or along the track side. The on board systems, can only be used by the train which supports it. The advantage is the increase of the efficiency. However, on board installations will increase the vehicle's weight. On the other hand, the wayside systems, can store the regenerated energy when nearby trains are applying regenerative braking. For this reason, it is important that these systems are installed near stations, so the stored energy can be reused by other trains. The main advantage is the possibility to recover from multiple braking trains at the same time, however, these solutions are less efficient due the transmission losses on the power line [29] [7].

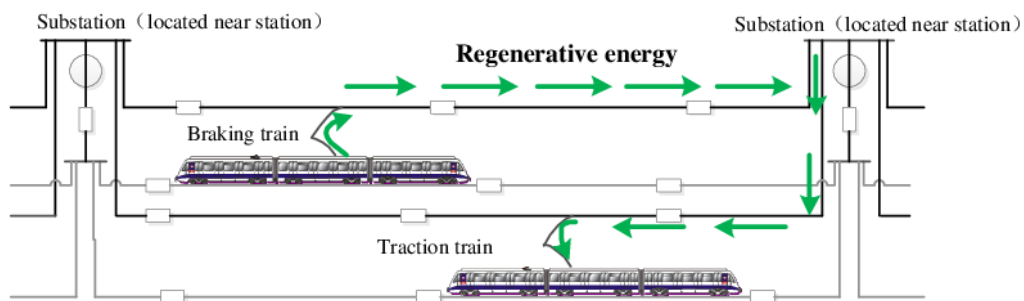


Figure 2.6: Immediate energy exchange between trains by regenerative braking, from [29].

So, this concept, working without storage equipment, as shown in figure 2.6, have some constraints, when a train is braking on the track, the other train should be in acceleration, in the other track, at the same moment. If there is no train in traction movement to receive the energy from a braking train, this energy is wasted, by a proper dissipation to earth [29].

With the very frequent starting and stopping of trains, it was found that 53% of the total energy consumption will be released during the braking stage. By subtracting the loss of motion resistance and mechanical braking, there is 22% of the energy consumption that can be restored by electric regeneration. These values occur only if the rectifiers are installed at proper locations along the line [7].

In conclusion, the trains should be matched in the proper timing and in space. In other words, the strategies are [7] [29]:

- the optimization of the train timetable;
- rectifier substations installed at proper locations;
- storage systems installed near stations.

2.1.6 Location of the power substations

An easy method to locate substations is to place them near the stations because it is where the power demand is high. However, civil constraints might be a problem.

Study optimization techniques for substation placement for DC traction systems have been developed along the years, and it is extremely important to apply those techniques or improve them.

Some research papers had the objective to optimize these placements. As previously mentioned, the author from [7] suggests placing the substations optimally for an accurate energy regeneration. The author from [19], suggests an algorithm to optimize a traction system for personal rapid transit, with the objective to minimize the energy losses on the network. This method locates the power supplies optimally for load balancing and uses an iterative approach based on the *virtual isolation* concept between substations. Basically, the optimal location of the substations is according to the geometric environments and the load power, in order to minimize its power rating. Although, this method doesn't consider some electrical requirements, regarding for example, the maximum drop voltage in the contact line.

2.2 Existing Simulating tools

The advantage to simulate electrical traction systems is the support to study and evaluate the best electrical configuration for a system, comparing different scenarios.

The simulators take into account the vehicle movement characteristics and the electrical power supply behavior in each instant.

The aspects that affect a supply system behavior are the interactions between the rolling stock, the route, the substations and other equipments. These informations provide a large amount of data and complicated calculations must be done by the software simulator tools [21].

The figure 2.7 shows a schematic that represents the process design simulate a system.

Modeling a railway system requires two sequenced calculations, the mechanical and then the electromechanical. Simulating a mechanical system, means calculating the train

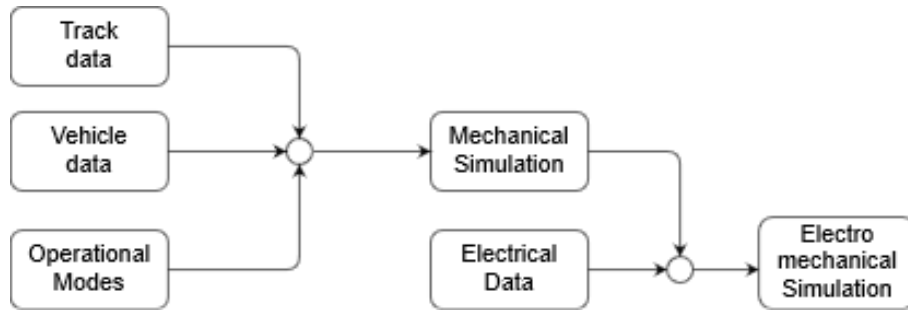


Figure 2.7: Process during the operation simulation

motion along the track, using ideal electrical conditions, without losses and considering that there is no drop voltage in contact line. It allows the user to decide properly the simulation time to use in the complete electromechanical simulation. In this last, it is needed more time to simulate, because means solving the power flow by considering all the inputs. So, optimize the simulation time is fundamental to save time during an optimization process.

Also, to use the right data from the vehicle, the general software tools allow full specifications to be inserted, which represents the system load representation.

The general parameters, used in the simulators, are indicated in table 2.1.

Table 2.1: Usual input data used by existing simulator tools

Track	Vehicle	Electrical
Stations	Weight	Traction transformer
Curves	Traction and braking effort	Positive line resistance
Slopes	Maximum speed	Negative line resistance
Speed limits	Auxiliary consumptions	Energy storage
Tunnels	Regenerative braking	Shunt connectors

The tool developed in this dissertation allows the user to insert some of these inputs, mentioned in table 2.1, such as regarding the track: stations, slopes and speed limits. All the inputs regarding the vehicle, refereed in table, can be inserted, unless the regenerative braking. Regarding electrical data, is possible to introduce almost all of these inputs, considering the simplifications, such as, only is possible to consider one shunt at middle distance between the positive network from electrical sections and the power supply uses

an ideal voltage source. Energy storage are not considered in the electrical model of this software tool.

The software tool of this dissertation unlike others, optimize automatically the traction system, giving it the best substations' traction group nominal power values, the parallel feeder cable cross section area and the position of the intermediate substation.

2.2.1 Existing simulating tools

Generally, the existing simulators can perform realistic electro-mechanical simulations for AC/DC railways, inclusive light rails, metros or trolleybus systems. Usually, they provide the analysis of system performances and their consumptions.

Below are stated the current commercially available software tools and they are mostly used by traction systems engineers.

- TrainsRunner, by Setteidea Srl, from [24];
- OpenTrack and Open Power Net, by Technical university of Zurich, from [20];
- TrainOp, by LTK Engineering Services, from [16];
- Sitras Sidytrac, from [27];
- EtraX, from [10].

The essential features of these softwares that allow the development of the traction model accurately, are the user-friendly graphical interface, simulating signaling systems, evaluation consumptions, simulate failures conditions, etc. Figures 2.8 and 2.9 show graphical interfaces that allow the user an overall graphic visualization of the system.

The signaling systems are useful tools, because allow simulating eventual train stops, that usually potentially lead to higher consumption levels during an operation.

On other hand, there are some limitations associated to these softwares such as the lack of automatic solvers to optimize the systems. So the users iteratively optimize the systems by consecutive electromechanical simulations. Also it is not usual, simulators consider an integrated economical solver, that theoretically would helps the users to study the configuration system impact on the solution costs. Also, it is not usual these tools to support simulate the medium voltage network in order to study the influence on the DC traction system.

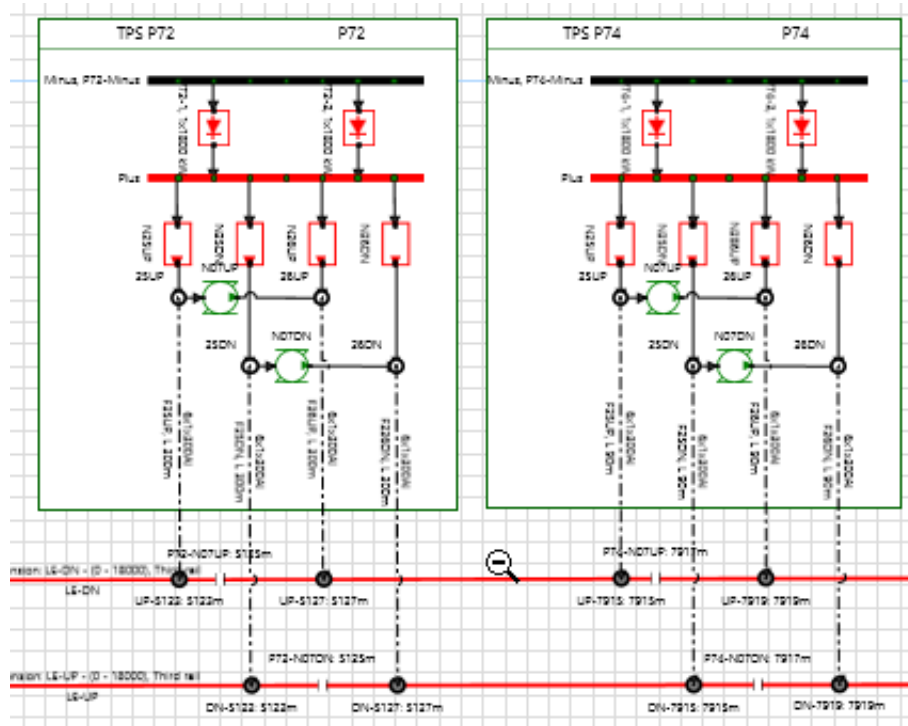


Figure 2.8: Trainsrunner design interface, from [23]

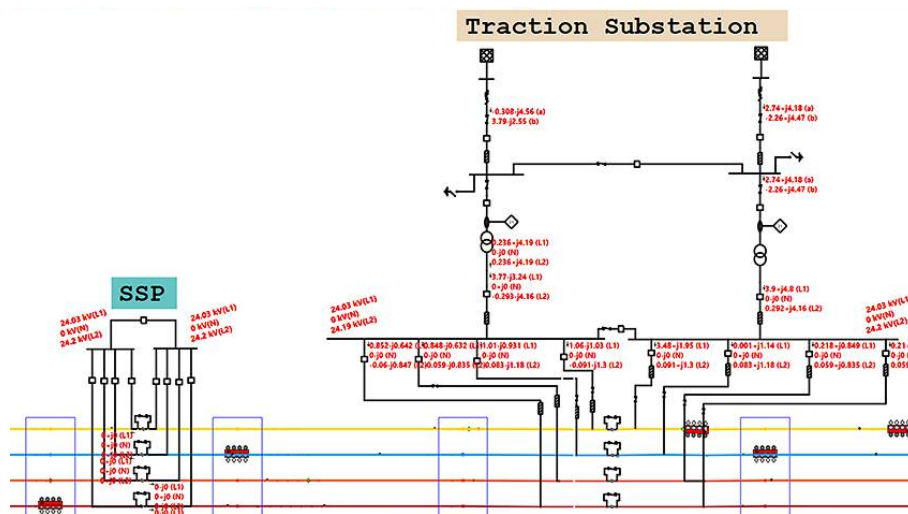


Figure 2.9: eTrax design interface, from [28]

Table 2.2 shows the main features and the constraints, of these existing software tools.

Table 2.2: Main Features of existing simulator tools

Simulators/ Features	eTraX	OpenPower	Trains Runner	Sitras Sidytrac	TrainOp
Evaluate consumptions	✓	✓	✓	✓	✓
Evaluate equipment losses	✓	✓	✓	✓	✓
Regenerative braking	✓	✓	✓	✓	✓
Harmonics results	✓	✓	✓	✓	✓
EMC results	✓	✓	✓	✓	✓
Automatically generates optimal power configurations	✗	✗	✗	✗	✗
Automatically generates the optimal electrical sections lengths	✗	✗	✗	✗	✗
Automatically generates the best configuration taking losses into account	✗	✗	✗	✗	✗

2.2.2 Projects designed by software simulators

In this section are presented two recent railway projects, where it was been used simulating tools.

In 2015, LTK Australia using the simulator TrainOps, simulated and studied the Melbourne tram railway, in Australia. The main goal was to report the issues and generate potential traction power upgrades to accommodate 110 new E-Class trams. These tram railway system are considered to be the longest in the world, with 250 km of double tracks, with 24 routes, 1679 passenger stops and a fleet of nearly 500 vehicles. After identifying 33 potential traction power upgrades, including new substations TrainOps was used to quantify the criticality of each potential upgrade. This study allowed decision makers to confirm the minimal requirements to introduce the new, more power demanding trams [15].

In 2017, TrainsRunner was used to simulate the Odense Light Rail, in Denmark. This system has 14 km of line, 26 stations and 14 vehicles to operate in the line. The DC supply system is composed by eight traction substations, located along the line. It is expected this system will carry 34 thousand passengers daily and is planned to be operational by the end of 2020 [9].

2.3 Genetic Algorithms

Software simulator tools usually don't have as a feature the application of genetic algorithms, although this dissertation looks to apply genetic algorithms as a method to solve optimize the systems configurations, finding optimal solutions.

Genetic algorithm are based on natural evolution, appreciated as a simple and consistent mechanism, that can be used to optimize models. Independent of the initial conditions of the algorithm, it generates high quality results, the reason why this mechanism is considered as consistent.

The genetic algorithm's main focus is the creation of descendants using recombination operators. Besides that, the mixed use of the mutation operators recombinations allows for the balance of two apparently conflicting goals: The best solutions harnessing and the search space of exploration. Thus, the genetic algorithms find the optimum point based in a candidates solutions population, and not just using a single point, using probabilistic transition rules [18] [12].

In figure 2.10 can be seen the flowchart regarding a classic genetic algorithm.

The traditional AG follows the following steps:

1. The initial population of chromosomes is generated by an aleatory process;
2. The population is evaluated according to its fitness, where each chromosome receives a value, which reflects its quality relatively to the problem's solution;
3. Chromosomes are modified by genetic operators, with the purpose to modify the population;
4. Then is created a new generation, taking the previous step into account ;
5. Steps 2 and 4 go in loop, until the satisfied solution has been reached.

Applying GA in optimization problems has been largely used, although it is important to correctly define the input parameters, which depends on the specific problem to be handle. The following list shows these parameters [12]:

- **Population:** The population size affects directly the GA global performance and effectiveness. The population with few individuals leads to a small search cover, which lowers the performance. On the other hand, a population with many individuals, ensure a higher problem coverage and reduces the probability of the algorithm to converge to local solutions, instead of global solutions. Typically, the usual common values are between 20 and 200 individuals.

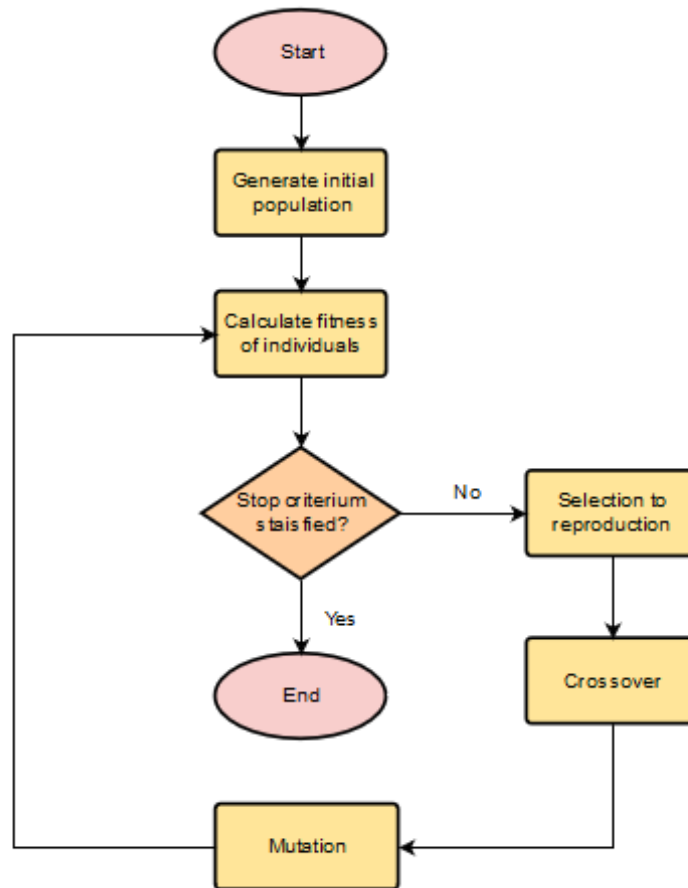


Figure 2.10: Flowchart of GA System, adapted from [12].

- **Number of generations:** The number of generations are associated with the population size and the computational available time for the algorithm execution. There are no common values for this parameter.
- **Cross over:** GA may suffer with the premature convergence of the algorithm, when the crossing over rate value is inappropriately defined. If this rate is too high, individuals with good fitness evaluation are repeated. Otherwise, if it's too low, the algorithm runs very slow. Typically, this rate is situated between 70% and 85%.

Genetic algorithm presents to be a potential technique to apply into the simulating tool of this dissertation. It will allow to find the optimal configuration, that is the less costly solution, that includes the estimated cost for losses along the distribution system.

PROPOSED DESIGN METHODOLOGY

This section introduces the DC traction system model. It is described the algorithm and showed the mathematical equations used to compute the model and simulate an operation in a DC railway system, take into account input data, such as, a vehicle (metro or light rail), track data and operation modes. This model takes into account the computed characteristics from the route and it is studied the traction behaviour with the respective electrical system. The purpose of this model is to allow that the tool simulates the model and generates the less costly configuration, that also comply with the electrical requirements. These costs take into account the investment cost in equipments and DC losses in the transmission sytem.

This model is based on a traditional DC traction system, where one vehicle operates along a route composed by a feeding power system, with three substations, computed as three voltage sources, and a typical electrical distribution system composed by a contact wire and a parallel feeder cable, which were computed as electrical resistances.

3.1 Model

The figure 3.1 shows the high level process flow of the simulation used in this software tool. This tool allows to simulate a vehicle operating along a route, fed by a traction supply system.

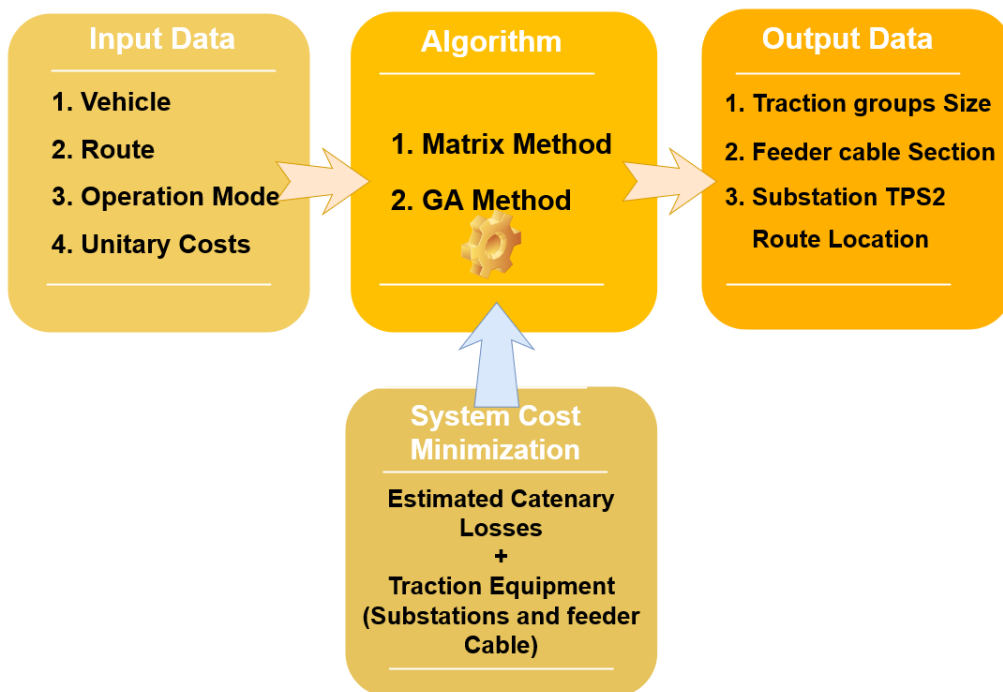


Figure 3.1: High Level Simulation process flow

The traction supply system, is composed of three consecutive substations, TPS1, TPS2 and TPS3 and a catenary system composed of a 120mm^2 contact wire and a parallel feeder cable, that will feed the vehicle that operates in a route. The route is represented by the slopes, speed limitation and passenger stations (ST). In figures 3.2 is shown the several parameters in study.

To comply with the losses minimization from the distribution system and to find the possible minimum cost for the traction system, the simulation runs in an algorithm loop process that evaluates the best configuration for the traction system. The configuration is related to the follow variables: the best section for the parallel feeder cable and the best position for substation TPS2. In figure 3.2 is shown a schematic of the traction system model in analysis.

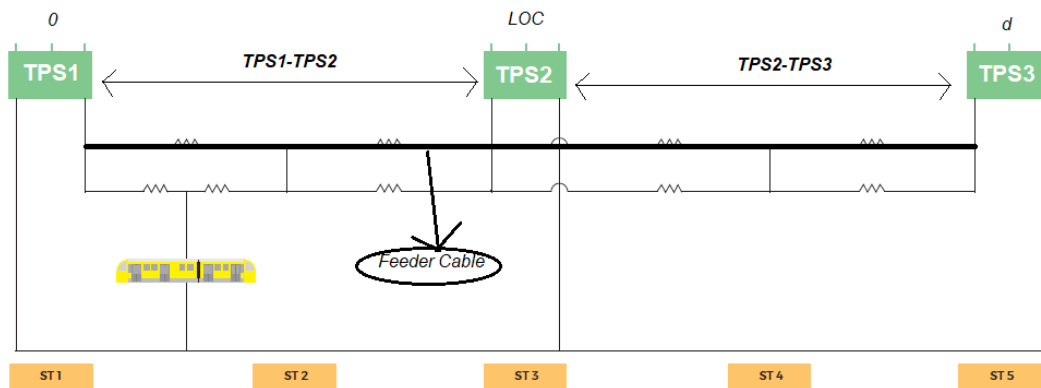


Figure 3.2: DC traction system considered

This process takes into account the system's life cycle. That means, the losses cost are estimated for this life cycle, defined by the user in the beginning of simulation. The algorithm evaluates the best system's configuration take into account the losses in the electrical distribution system in this considered period.

An Excel file is used to allow the user to insert the needed input data. The simulation software import these data, in every iteration to simulate the operation with the respective configuration. This interface connection is shown in figure 3.3.

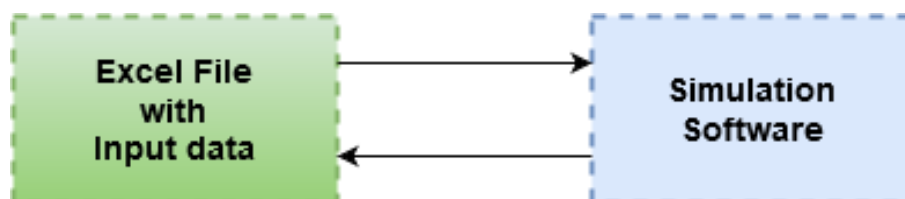


Figure 3.3: Representation of the interface between Excel and the simulation software

This input data are: the length of the route which also include the slopes, speed limits and stations. The vehicle specifications and the operation mode data are also exported.

The vehicle is the only consumer of this system, when he requires power and current flows trough the transmission system from substations, the resistance on the contact line will varies. This will affect the voltage drop in the contact line. Therefore, the current

needed by the vehicle to operate results from the travelling speed and the tractive or braking effort that is produced. So, to simulate the vehicle was used a dependent current source, that is resulted from the electrical power and the contact line voltage drop in each moment of the operation.

In figure 3.4 can be seen a light rail fed by an overhead contact line system.



Figure 3.4: S200 high floor light rail vehicle, from [25].

The input data regarding the vehicle are the weight, the acceleration and deceleration values, the absorbed current limitation, traction and braking effort limitation curves, running resistance and the auxiliary systems power (A/C system, lights, doors, etc). These inputs are detailed in section 3.1.2.

The speed desired along the route and vehicles frequency belongs to the operational mode inputs, which its control is detailed as follows:

Firstly, the user should insert the limits of speed along the route, this way creating the speed limits profile in each position. It is intended that the vehicle follow this reference profile, so to modulate the control the speed was used, a PID block, as can be seen in figure 3.5. This block receives the performed simulated speed from the dynamic equations block and it will compare with the reference speed. Then is generated the proper value for traction or braking force.

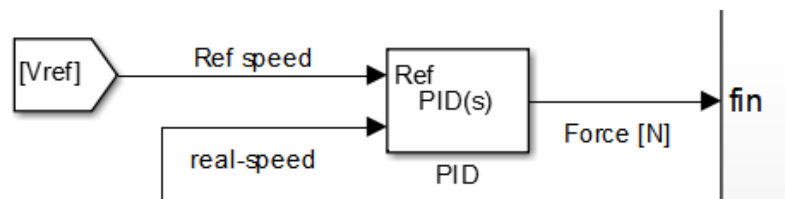


Figure 3.5: Simulink blocks used to model the speed control system using a PID

An example of this control of speed can be observed in figure 3.6. The blue line represents the maximum admissible speed for each position. The red line, is the speed performed by the vehicle. As can be seen, the variation of speed is linear, because it is considered a constant value for acceleration and deceleration. To ensure, that the vehicle doesn't exceed the speed limits, it is previously calculated, the exact moment necessary to start braking the vehicle, considering the deceleration maximum value.

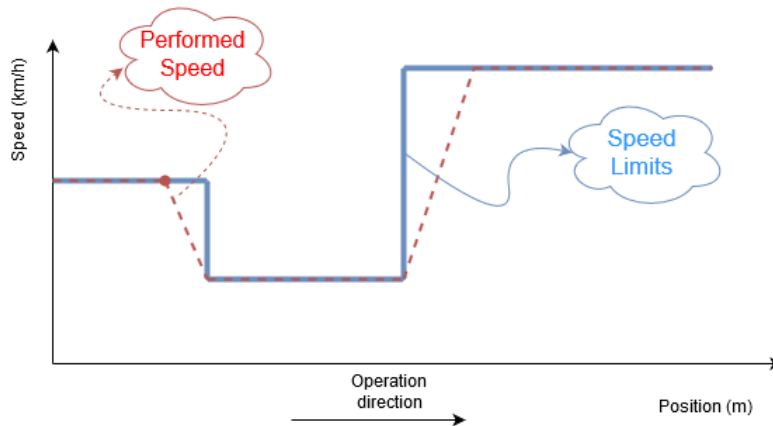


Figure 3.6: Example of the speed control results

The user should specify the desired Headway, which, globally is the route capacity of the transit system. The headway is the time difference between two consecutive vehicles. In this dissertation, the headway value is proposed to determine the number of trips during the operation life cycle. This data allows to calculate the consumption based on the number of operations. It isn't considered more than one vehicle at the same time in the route. This input is included in the operational mode inputs. Figure 3.7 graphically shows the headway meaning.

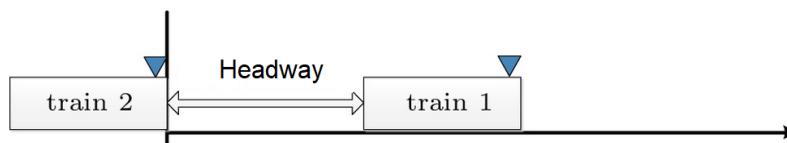


Figure 3.7: Headway between two vehicles. Adapted from [14]

The figure 3.8 shows a high level simulink model representation. The simulink uses the electrical configuration reference code that allows to perform a simulation, using the electrical power that the vehicle needs to run properly.

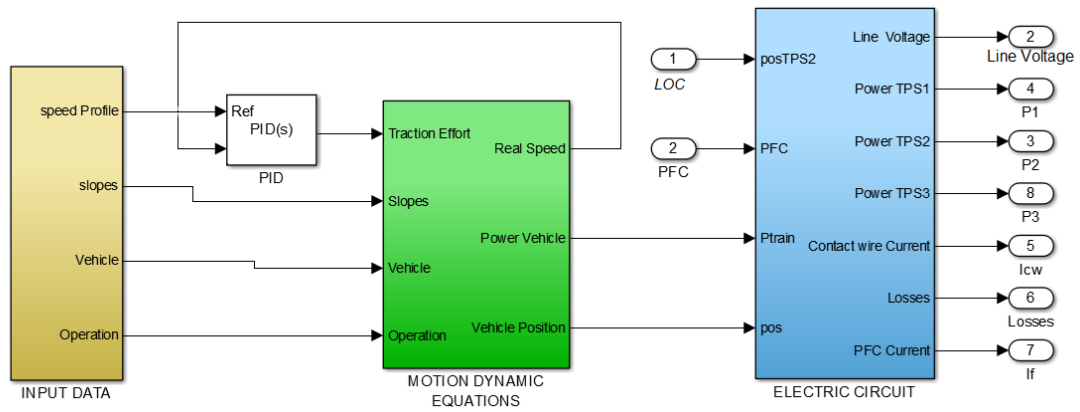


Figure 3.8: High level simulink model representation

3.1.1 General synthesis methodology

The method used to find the system minimum cost is defined in the simulation software environment. This cost is achieved after the simulation optimizes the traction supply system.

This optimization is based on choosing the best traction electrical supply configuration, which is formed by two variables: the TPS2 location in the route, and the cable to use as parallel feeder cable. Those two variables are identified by the reference code "LOC"(Location) and "PFC"(Parallel feeder cable), respectively.

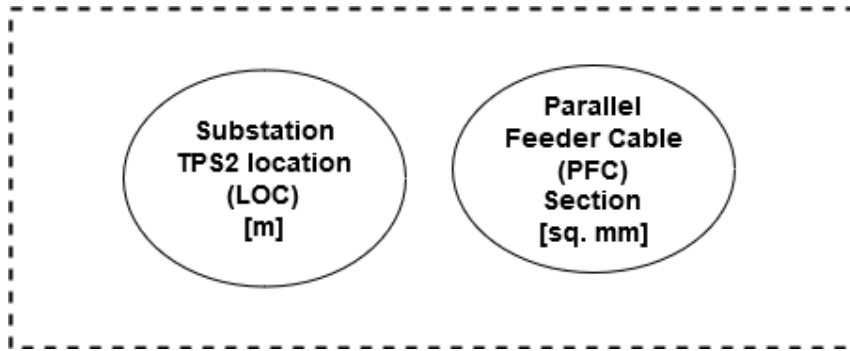


Figure 3.9: Optimized variables used in simulation, (LOC and PFC).

The first step of the algorithm, after getting the mechanical and electrical input data, is simulate one operation by using the configurations, regarding the power supply system. It is expected, in the end of simulation, achieve the best configuration among the considered hypothesis.

In this case, the best sample space representation of the problem is using a two-way table, as can be seen in figure 3.1. This table was created by using two variables, PFC and LOC. So, it leads at 72 hypothesis that potentially can be the solution, it means, the less costly configuration, which includes the estimated losses cost.

Table 3.1: Two-way table that represents the sample space relatively the system configurations

LOC/PFC	1	2	3	4	5	...	10
0	(1,0)	(2,0)	(3,0)	(4,0)	(5,0)	(...,0)	(10,0)
120	(1,120)	(2,120)	(3,120)	(4,120)	(5,120)	(...,120)	(10,120)
185	(1,185)	(2,185)	(3,185)	(4,185)	(5,185)	(...,185)	(10,185)
240	(1,240)	(2,240)	(3,240)	(4,240)	(5,240)	(...,240)	(10,240)
...	(1,...)	(2,...)	(3,...)	(4,...)	(5,...)	(...,...)	(10,...)
Y=2x800	(1,Y)	(2,Y)	(3,Y)	(4,Y)	(5,Y)	(...,Y)	(10,Y)

It is pretended to achieve the minimum cost for the system by considering the configuration that minimize the losses and at the same time, using the lowest possible initial investment cost. The investment considered in this dissertation is settled in the initial of

times and includes the energy equipments that are inside the substations and the cable used as parallel feeder cable. To ensure the efficiency of operation, those equipments are sized in accordance to guarantee the trip conditions inserted, although, it is verified if there is overloads.

The equipments directly responsible to provide power for the line are the traction groups, which are composed by a traction transformer and a traction rectifier. so, they are chosen and sized take into account the operation consumption. In section 3.1.1.1 is detailed this process.

The figure 3.10 shows an example of a traction system power diagram. Those lines represents the power delivered by three substations, needed to ensure the operation, giving this way the energy the vehicle needs to perform properly, also includes the total losses

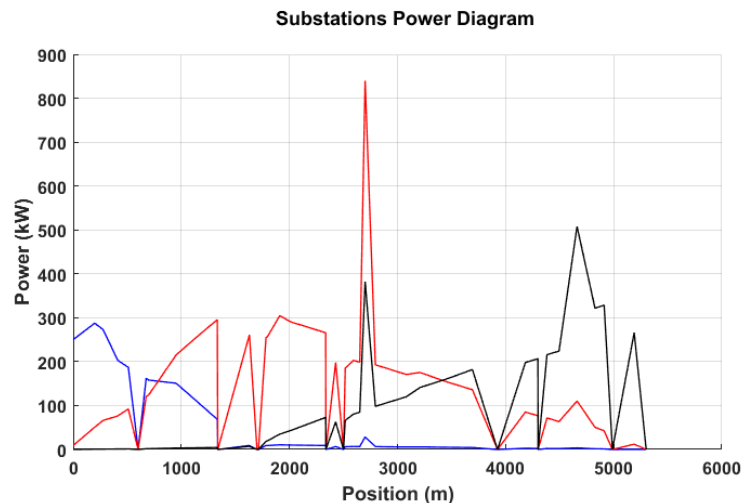


Figure 3.10: Example of consumption profile from three substations located consecutively in a track

The algorithm automatically incremented the traction groups, in substations, if needed, by incrementing the power capacity in equal values each time, in this case, 1000 kVA. So, consequently, it is quoted more traction groups to be added at the system's cost.

In figure 3.11 can be seen a substation single line diagram. As can be seen it is a basic representation of the components in a substation. The main energy equipments are considered in the quotation, in this dissertation, to estimate the overall substation cost. These components are: the traction group, composed by the traction transformer and rectifier, the medium voltage board, the low voltage system and the DC traction board.

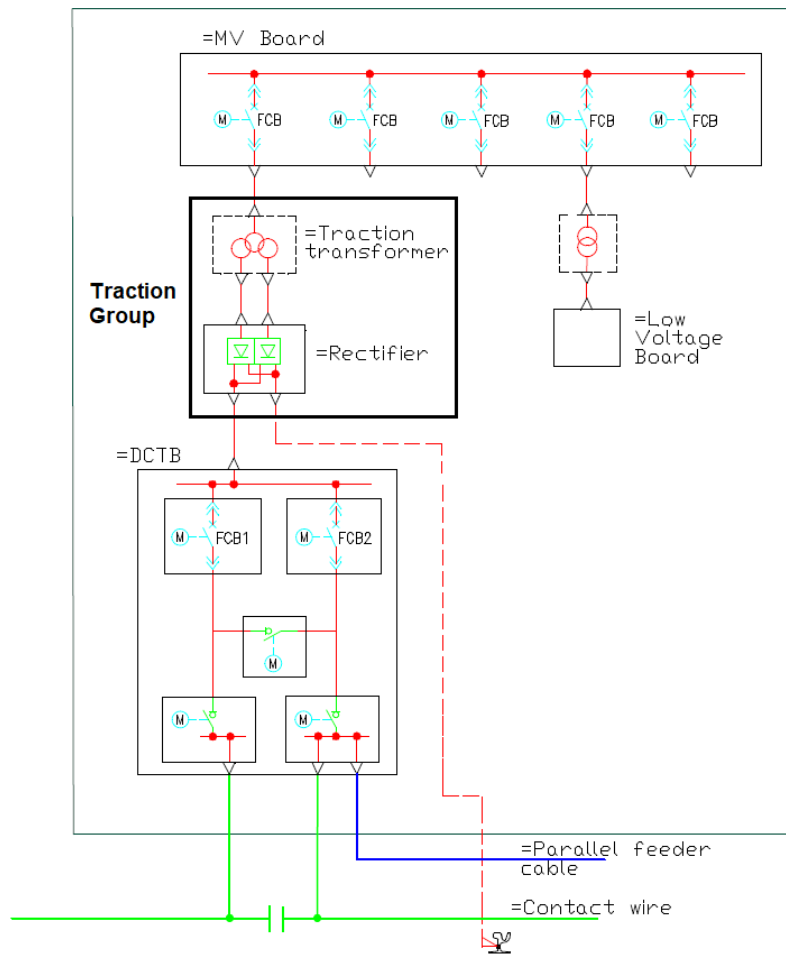


Figure 3.11: Substation single line diagram

3.1.1.1 Sizing the power supply system

The simulation automatically sizes the substations and the cable section to use as parallel feeder cable. The scale of the substations is by comparing the nominal power of the traction transformer and rectifier with the power diagram curve. This comparison take into account in complying with the minimum electric requirements, mostly used by design systems, that is regarding the load/time duration.

To develop these process that is usually implemented by railway designers, the simulated configuration will be evaluated acceptable if the following conditions are verified.

- The maximum permanent current in contact wire is lower than the maximum considered. If it was registered current overloads in contact line, it is increased the parallel feeder cable section, in order to decrease the resistance and solve the issue;
- The minimum contact line voltage is higher than 500V;
- The maximum permanent current delivered by substation is lower than 150% of the nominal value.

The figure 3.12 shows both the systems: the substations and the catenary system, which is composed by a contact wire and the positive parallel feeder cable.

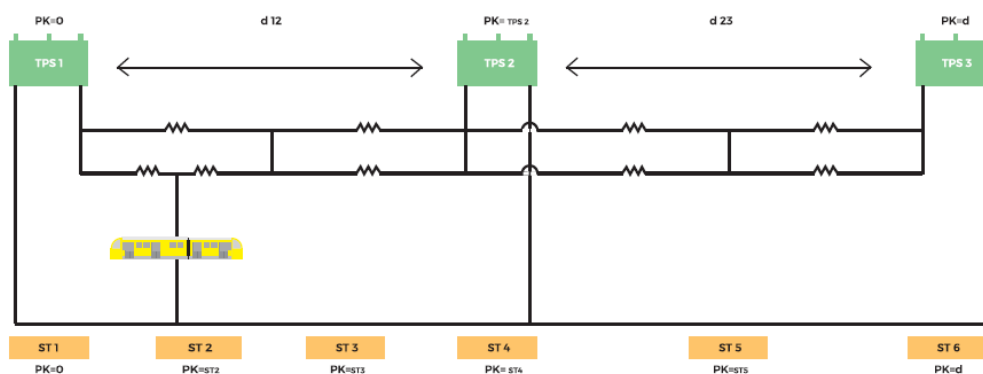


Figure 3.12: DC traction system

The substations locations in the track are compliant with the following:

- TPS1 and TPS3 have pre-defined locations: in the beginning and in the end of the route, respectively;
- Resulted from simulation are the best location for the intermediate substation (TPS2). It is considered, by simplicity, nine possible locations (equally spaced along the track). In figure 3.13 can be seen a representation of these possible locations, the referred percent values represents the distance relatively to the total length of the route.

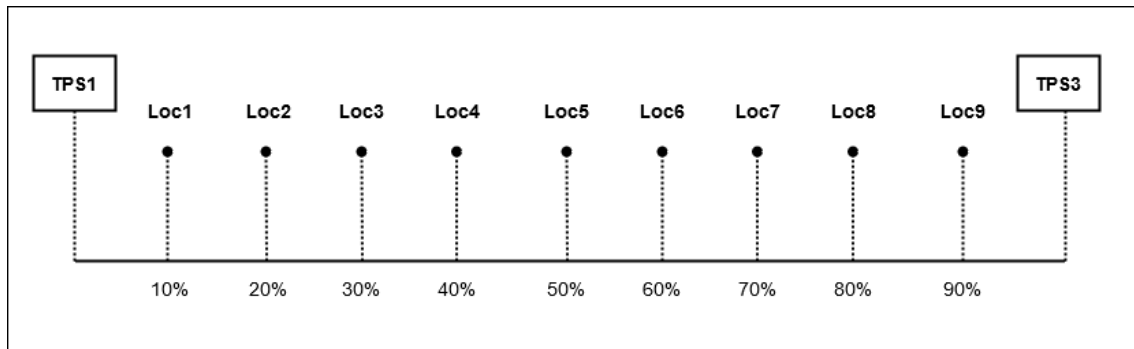


Figure 3.13: Representation of possible TPS2 locations in percentage value of the total length of the route

The parallel feeder cable belongs to the distribution system, which is also composed by a fixed 120mm^2 section contact wire. In figure 3.2 can be seen the cables input database, to use as parallel feeder cable, during simulation.

Table 3.2: Parallel feeder cable used in the software tool

Code Id	Section [mm^2]	Resistance [Ω/km]	Maximum Capacity [A]
PFC120	120	0.22	380
PFC185	185	0.148	420
PFC240	240	0.074	450
PFC400	400	0.044	821
PFC630	630	0.028	580
PFC800	800	0.022	620
PFC2x800	2x800	0.011	1238

3.1.1.2 Investment cost in equipments

The estimation cost for traction equipment is based on the equipment's unitary prices, that are predefined in the excel file. The values considered in this study are showed in table 3.3 and 3.4.

Table 3.3: Substation Equipments considered and respective unitary prices

Substation Equipment	Unit Cost [€/km]
Traction Transformer 1000 kVA	30000
Rectifier 1000 kW	15000
Medium Voltage Board	50000
Low Voltage System	100000

Table 3.4: Considered cables and respective unitary prices

Cables	Unit Cost [€/km]
PFC120	1400
PFC185	1900
PFC240	2800
PFC400	2950
PFC630	5200
PFC800	6400
PFC2x800	12300

Figure 3.14 is an inside overview from a substation with the considered equipments referred in table 3.3. The Low Voltage System represents the overall low voltage equipments, such as, the switchboards, the UPS, the control system, the voltage limit device and the auxiliary transformer. Those equipments aren't the focus of this dissertation, the main intention in using them is to achieve a more estimated real cost for the substations.

Figure 3.15 is a representation of a typical electrification for a railway. The Parallel feeder cable, in this case the cable goes along the route by air, but it is common to see the cable going buried. Figure 3.16 shows a cross section of an insulated cable that is used as parallel feeder cable. In figure 3.16 can be seen a traction transformer.

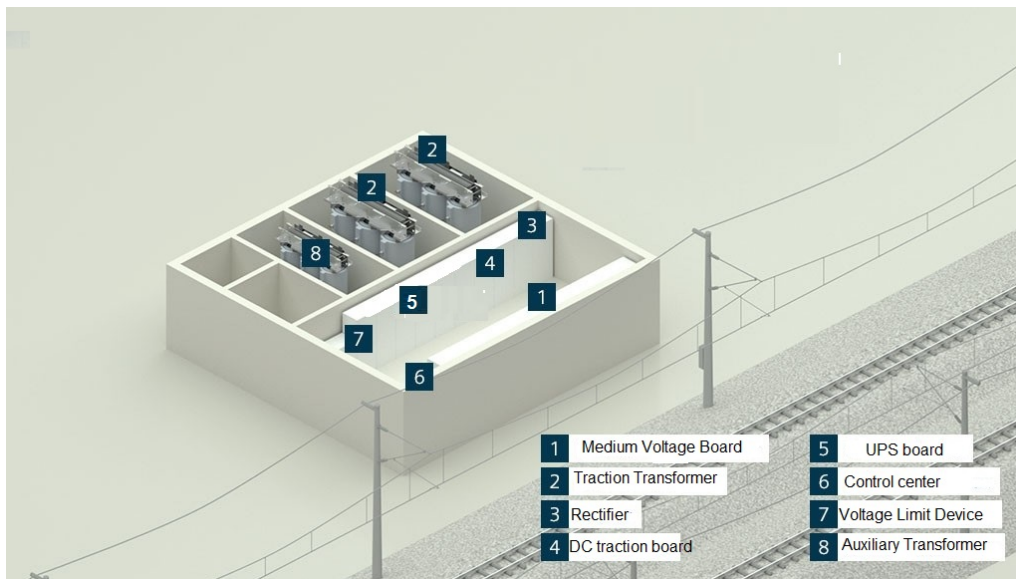


Figure 3.14: Inside overview of a typical traction power substation [Adapted from Siemens]

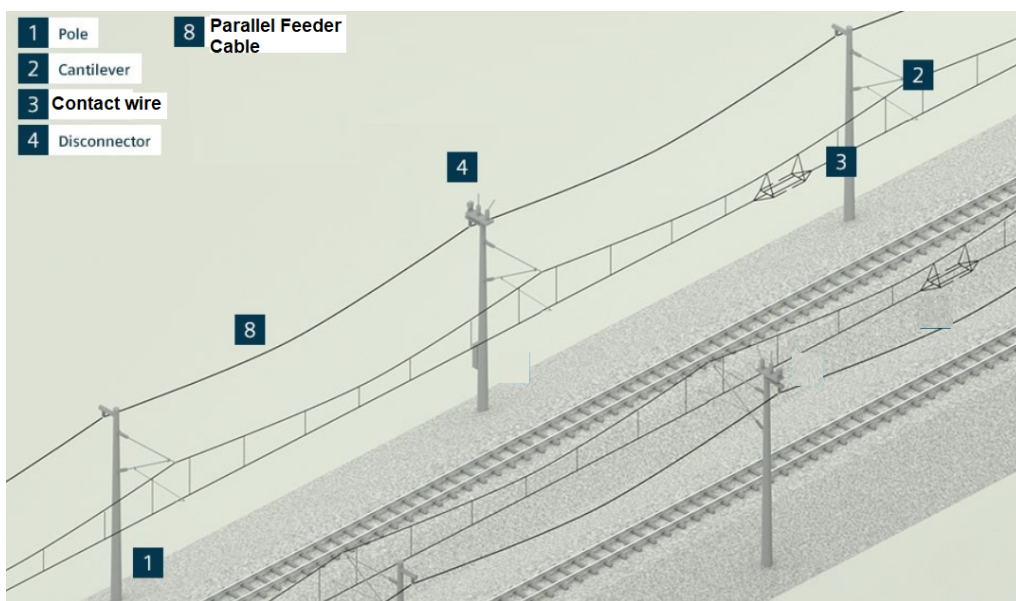


Figure 3.15: Typical Electrification of railway [Adapted from [26]]



Figure 3.16: Cross section of a feeder underground cable



Figure 3.17: Example of a Traction Transformer, from Efacec Power Solutions LinkedIn page.

3.1.2 Dynamic variables modelling

In this section can be seen the dynamic motion equations that models the system. The equation expressed in 3.1 is the Newton's 2nd law and it is the fundamental equation.

$$F_{in} - F_{ext} = m \times a \quad (3.1)$$

The acceleration is proportional to the resulting forces and it is dependent on the total mass of the vehicle. F_{in} relates the traction or braking effort required by the vehicle to overcome the resistive forces F_{ext} and operates. This parameter is introduced as a curve dependent on speed, as can be seen in figure 3.18 as example [13].

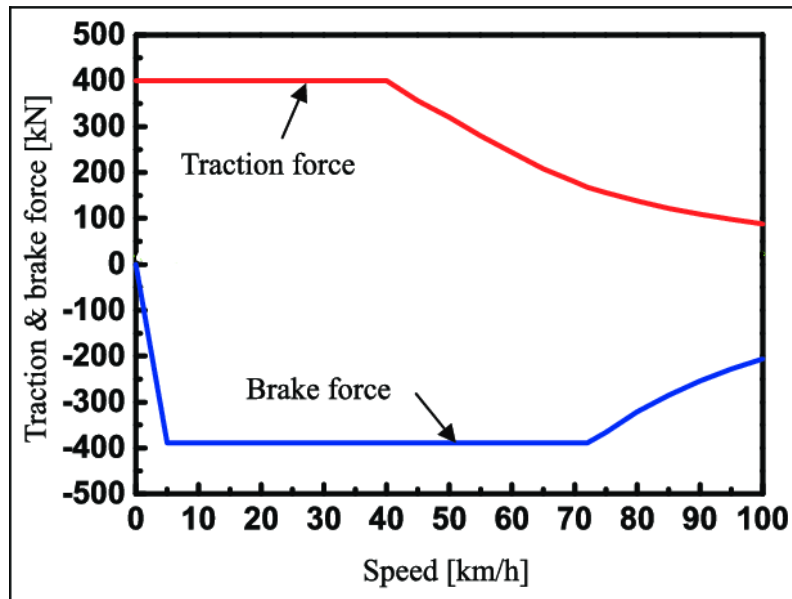


Figure 3.18: Typical traction and braking effort curves

In equation 3.2 can be seen all the drag forces used in the model. These forces are described in detail in sections 3.1.2.1 until 3.1.2.2, [17].

$$F_{ext} = F_f + F_a + F_d + F_c \quad (3.2)$$

3.1.2.1 Motion Resistance

Running resistance

Running resistance is given by an empirical formula, as can be seen in equation 3.3. This resistance depends on the vehicle weight, the mechanical frictions inside the vehicle, between wheels and rails and aerodynamic drags, [2] [22] [17].

$$F_f = A + BV + CV^2 \quad (3.3)$$

The coefficients A, B and C are constants and V is speed in m/s. These constant factors are obtained by fitting the coefficients of the Davis equation 3.3. These coefficients are

explained below.

The coefficient A is related to the drag between wheels and rails. Coefficient B comes from the quality of railway and the train stability. For this reason, they represent, the mechanical resistances of the vehicle with the railway. These terms have low relevance in low speed values.

At high speed, the term CV^2 , which is related to the aerodynamic resistance, becomes more relevant. This last term is largely affected by the existence of tunnels and the crossings with other vehicles, during the operation.

3.1.2.2 Declines Forces

During the passage through an up climb, the gravity force applies a drag force to the train motion. In case of a down climb, this force favors the motion. This force is expressed by the equation 3.4, [3], [17].

$$F_d = mg\sin(\alpha) \quad (3.4)$$

Where, $\alpha > 0$ in up climbs and $\alpha < 0$ in down climbs.

3.1.3 Electrical system modelling

The modelling of the electrical system has been carried out by using the package `sim-scape` from Simulink. The electrical model is mainly composed by a source system, with three substations and an electrical distribution system, composed by variable resistances, that carry the energy to feed the load, that is the vehicle.

The power flow is modeled using dependent current sources and an additional logic blocks that controls them. This logic allows to ensure that there is just one vehicle running during the trip and that at each moment this current source receives the proper data. The source system has been developed by making use of a DC voltage source and a resistance in series. Figures 3.19 and 3.20 shows a detailed image of the electrical circuit blocks from simulink.

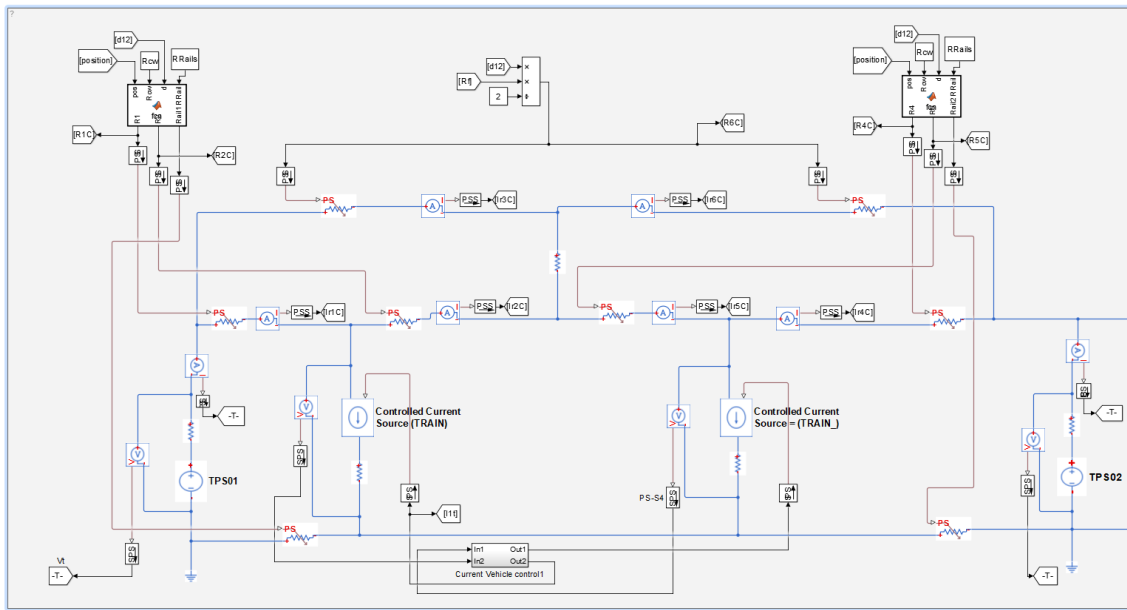


Figure 3.19: First electrical section circuit modelled in simulink

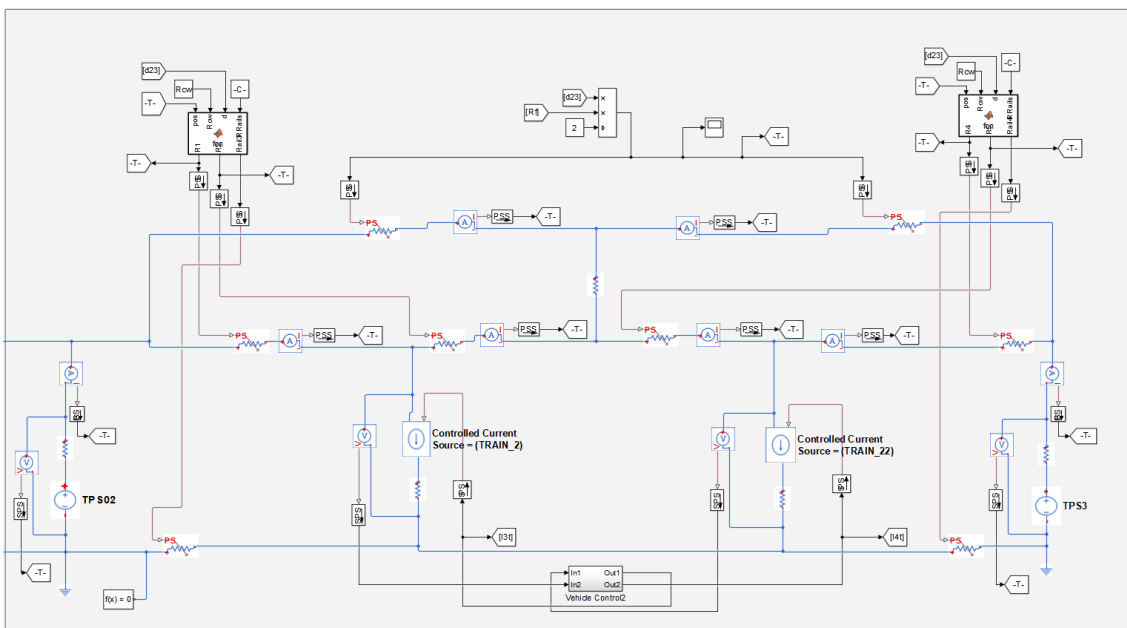


Figure 3.20: Second electrical section circuit modelled in simulink

The electrical power flow created by the vehicle has been simulated using the traction and braking force required and the speed that it goes, at each time. It was considered a yield value of 90%. So, the electrical power during traction and braking can be expressed by the equations 3.5 and 3.6, respectively according the operation state, during traction or braking.

$$P_{elect}(t) = \frac{F_{in}(t) \times v(t)}{\eta} \quad (3.5)$$

$$P_{elect}(t) = F_{in}(t) \times v(t) \times \eta \quad (3.6)$$

In figure 3.12 can be seen the representation of the traction system, including both systems: The supply system that is composed by three power substations, TPS1, TPS2 and TPS3. The distribution system is composed by the contact wire and the parallel feeder cable. Those two cables are shunted at middle way distance from substations, named feeder nodes.

The electric circuit is composed by two electrical sections, the first between TPS1 and TPS2 and the second between TPS2 and TPS3. Each one is mainly fed by two adjacent substations. Substations were designed using ideal 750Vdc voltage sources, each with 0.01 Ω/km internal resistance.

For example, when vehicle is moving between the beginning of the route and the shunt, the situation represented in 3.21 occurs. When the vehicle is operating after shunt, the resistances before shunt assumes constant resistance values.

Each feeder cable with different section is presented in the inputs file, as can be seen in table 3.2.

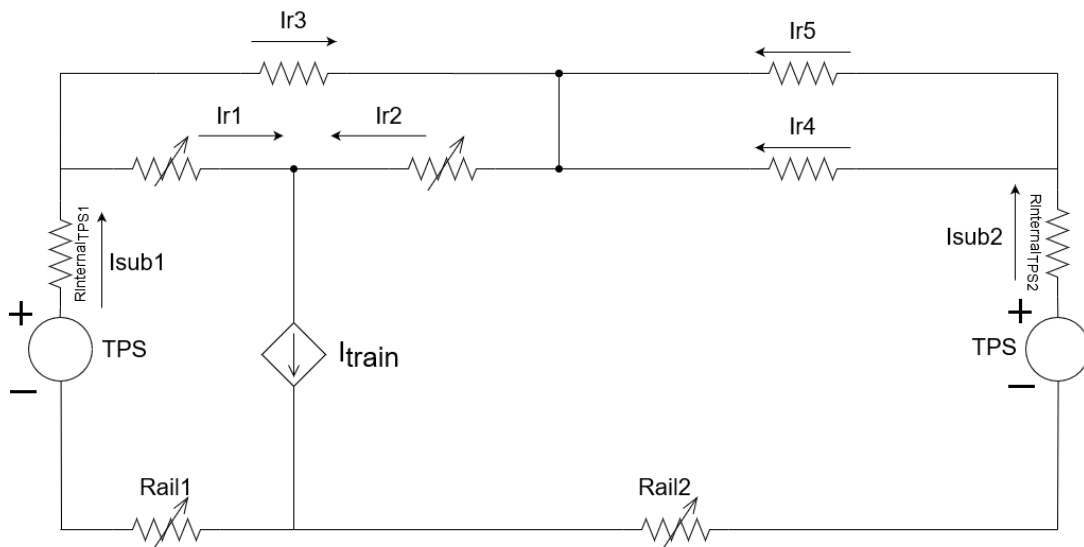


Figure 3.21: Electrical schematic model

$$I_{train}(x) = \frac{P_{elect}(x)}{V_{train}(x)} \quad (3.7)$$

3.1.3.1 Consumption and losses calculation

To ensure the operation, three substations are needed to provide sufficient energy. For this reason, consumption is calculated, as follows:

$$E_{TPS}(t) = \int_{t=0}^t \frac{P_{elec}(t) \times \Delta t}{3600} [kWh] \quad (3.8)$$

where:

$[\Delta t]$ - Sampling time considered, 1 second;

$P_{elec}(t)$ - Substation power in each moment.

Figure 3.22 shows an example of substations power diagram curves.

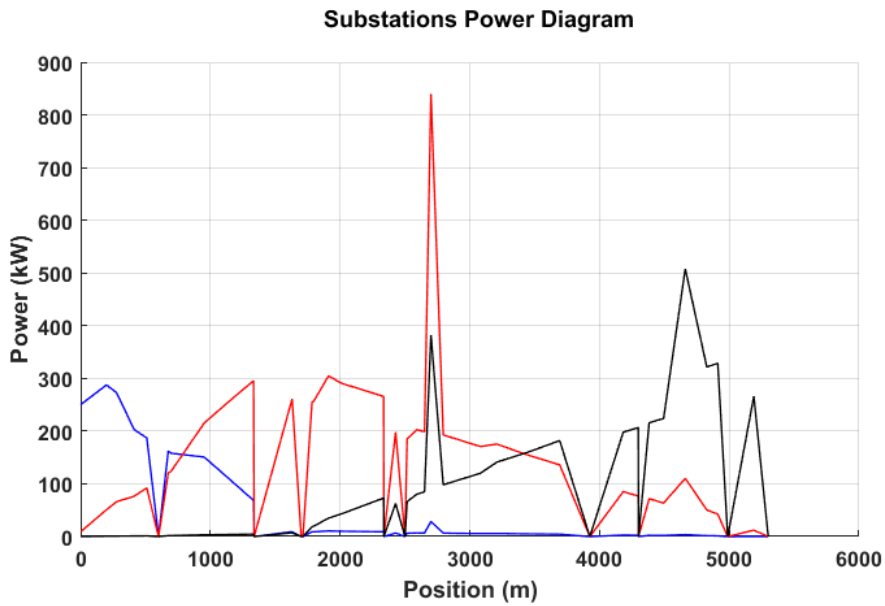


Figure 3.22: Example of power diagram from three substations

The losses are calculated as follows:

$$\begin{aligned} E_{losses} &= R_i \cdot I_i^2 \\ &= \frac{\rho \cdot \ell}{A} \cdot I_i^2 \end{aligned} \quad (3.9)$$

where:

ρ - Electrical resistivity [$m\Omega \cdot m$];

ℓ - length of the cable [m];

A - Cross Section of the cable [mm^2];

I_i - Current in each branch of catenary system [A].

The estimated energy cost consumed during a life time depends on the energy used from substations. So, to evaluate each configuration, firstly is considered the power diagram curves from each substation. It was considered the operation works during 18 hours a day with an ideal headway, during weeks and weekends, for the considered life time. These approximation is acceptable because the intention is to calculate the consumption worst case scenario.

So the annual energy consumed is expressed by equation 3.10.

$$E_{CONSUM} = \sum_{i=1}^3 E_{TPS_i} \cdot \frac{60}{HW} \cdot 18 \cdot 365 [kWh] \quad (3.10)$$

where:

$\sum_{i=1}^3 E_{TPS}$ - Sum of the energy consumption from traction power substations [kWh];

HW - Headway [minutes];

3.2 Financial evaluation

In this section is showed the financial evaluation of the model. This process aims to show the financial impact on the traction system configuration. All the energy is acquired from the same power source, even the energy that is wasted along the operation. So, these wastes are take into account in the total amount of the system cost.

The tariff considered to calculate the energy cost, is 0.1 €/kWh. This value is based on the values applied at Portugal industrial consumers, which is possible to see in table 3.5. In the algorithm of this dissertation has been applied constant refresh rate of the energy price: 4%, in each year. This value has been chosen in order to be conservative.

Table 3.5: Tariff for sale to final customers in MV [Translated from ERSE, 2018b]

MV long uses Tarrif Active Energy (€/kWh)	
Description	Prices
Peak hour	0,1382
Partial Peak hour	0,2201
Off Peak hour	0,0777

The equation used to calculate the final estimated minimum cost is showed in equation 3.11. This equation is the sum of the cost in equipments (substations and catenary) and the estimated consumption and losses costs.

$$cost = Cost_L + Cost_{PFC} + Cost_{TPS} + Cost_{CONSUM} \quad (3.11)$$

where:

- $Cost_L$ - Losses estimated cost;
- $Cost_{PFC}$ - Parallel feeder cable investment cost;
- $Cost_{TPS}$ - Substations equipments investment cost;
- $Cost_{CONSUM}$ - Consumption of the operation cost.

3.3 GA Method

In this section is presented an alternative method to find the optimal solution. This method applies genetic algorithm.

3.3.1 Genetic algorithm

The first step to apply the genetic algorithm is initiate the parameters for the function $ga()$. It is used to obtain the desire solution: the minimum cost for the traction system. Optimizing two variables: the distance between substations and the section for the parallel feeder cable.

Defining bounds for the variables in optimization allows the user to exclude some configurations from the simulation, for some reason. This way, the data sample is shortened and possible cause a speed up on the simulation.

In table 3.6 is possible to see those bounds, in this case $LOC1$ and $LOC12$ is the location for substation $TPS2$ in the route and $PFC1$ and $PFC2x800$ is to the section for parallel feeder cable.

The last column, **vector position**, shows the vector that allows the algorithm, to get the respective input values of a configuration, in order to perform a simulation.

Table 3.6: Parameters bounds used in function @ga

	Item Description	Value [m] or [sq. mm]	Respective Config Code Id	Input parameters Vector position
LB	Position TPS2	530	LOC1	1
LB	Section feeder cable	120	PFC0	1
UB	Position TPS2	4770	LOC9	9
UB	Section feeder cable	1600	PFC2x800	8

The optimization has been carried out of the follow specifications: *Generations*, is the maximum number of generations considered for the algorithm and it is related to the size of the population, so, in this case, 5 generations shows to be enough to achieve the solution. The value of the population size has been 12.

The algorithm use three constraints, seen as follows. If one configuration doesn't comply with the restrictions, the algorithm penalizes this solution, increasing the cost in very high values.

- $V_L > V_{min}$;
- $I_{EQ_{PFC}} < I_{EQ_{PFC}}$;
- $I_{EQ_{CW}} < I_{EQ_{CW}}$.

where:

- V_L - Line voltage
- V_{min} - Minimum line voltage, 500 V for 750V rated.
- $I_{EQ_{PFC}}$ - Equivalent Current in each feeder cable branch.
- $I_{EQ_{CW}}$ - Equivalent Current in each contact wire branch.

3.3.1.1 Cost Function

The cost function is, in fact, a performance finder, which tends to be a way to choose the best solutions, based in the value of this function. Equation 3.12 is a representation of the objective function, as can be seen, the estimated cost for parallel feeder cables, plus the cost considered for the wasted energy by catenary. Then is added the cost from the consumption and the investment in equipments for the substations.

$$cost = Cost_L + Cost_{PFC} + Cost_{TPSS} + Cost_{CONSUM} \quad (3.12)$$

where,

- $Cost_L$ - Losses from catenary: contact wire and parallel feeder cable;
- $Cost_{PFC}$ - Parallel feeder cable Investment;
- $Cost_{TPSS}$ - Traction Power Substations equipments Investment;
- $Cost_{Op}$ - Operation Energy consumption.

CASE STUDY

In this chapter is presented the results from simulations and respective analysis. It is showed a comparative study between two case studies and it is evaluated and studied the relative best solution for the traction system. It was used the software tool described in the previous chapter to simulate the different configurations. Firstly, the considered inputs are showed and then can be seen the obtained results from simulation. After the respective analysis, it is shown the effect of the genetic algorithm to estimate the traction system cost, presenting the best cost-benefit solution.

4.1 Resume of the cases studies

It is showed two case studies, named SC1 and SC2, each one includes a group of traction system configurations, aleatory chosen, in order to simulate and compare different scenarios regarding power supply. The main difference is the parallel feeder cable used and the intermediate substation location. The purpose of these comparative analysis is show the importance of optimizing and defining, conscientiously the traction system supply configuration. So, it is showed the impact in use these configurations on the wasted energy by catenary. To conclude the analysis, it is showed an economical comparative result between the configurations.

To simulate those configurations, firstly, it is showed the considered input data and considerations, then are showed the outputs, such as, the speed and acceleration profiles, the vehicle position and vehicle consumptions along the route. As the vehicle operation is always in same conditions and assumptions, the load consumption is the same in all configurations, although changing the configuration will impact on the power supply behaviour. To study these impact electrical outputs are used and showed, such as, the

contact wire drop voltage and current values and substation consumptions.

The tool has been used to estimate the minimum cost involved in the system (the investment in feeder cable and the losses estimated cost from the catenary system). The variables considered to this study are, once more: the location for substation TPS2 *Loc* and the section for parallel feeder cable *PFC*. It is pretended the algorithm finds the configuration [*Loc*;PFC] that leads to the minimum final cost.

4.1.1 Case Study input data

In this section is presented the inputs considered in the simulations for the case studies.

In table 4.1, is possible to see the speed limits profile in kilometers per hour in each position of the route and the respective resulted graph.

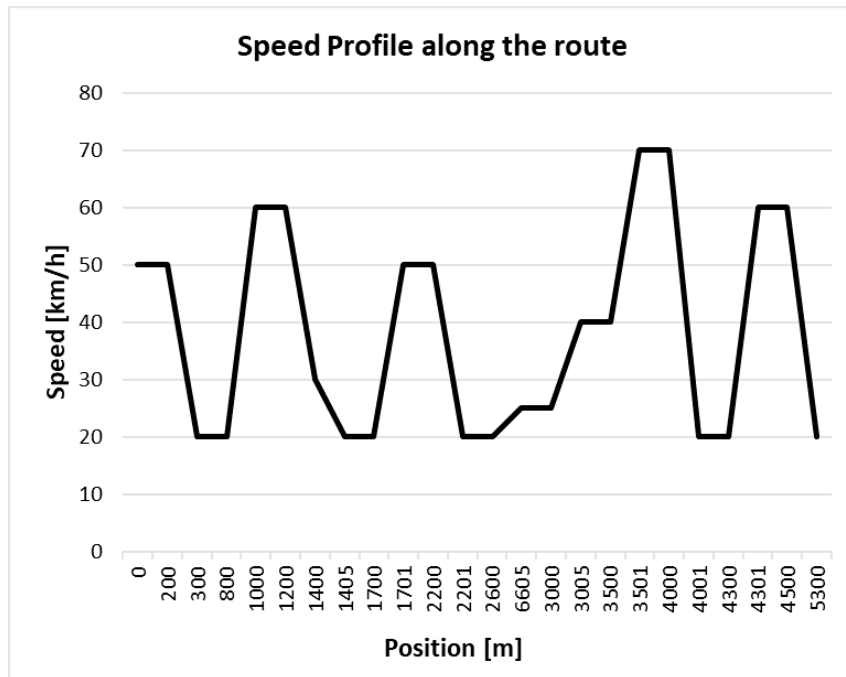


Figure 4.1: Image of the inserted speed profile

Table 4.1: Input speed profile

Position [m]	Speed Limits [km/h]
0	50
200	50
400	20
600	20
800	20
1000	60
1200	60
1400	30
1650	20
1700	20
1800	50
2000	50
2200	50
2350	20
2400	20
2600	20
3000	25
3500	40
3700	70
4000	70
4100	20
4300	20
4500	60
5100	20
5300	20

Table 4.2: Stations considered in simulation

Position [m]	Station Name
0	Station 1
600	Station 2
1700	Station 3
2500	Station 4
4300	Station 5
5300	Station 6

In table 4.3, can be seen the characteristics of the vehicle. It is recommended the user inserts the worst case data, regarding the consumption, that, in this case is considering the vehicle are fully loaded, so the weight corresponds to the vehicle tare plus its maximum capacity and the acceleration and deceleration values are the highest values that are allowed by the vehicle driver.

Table 4.3: Vehicle considered in simulation

Data	Unit	Value
Weight	[kg]	123072
Constant Coefficient	[N]	2199
Linear Coefficient	[N]	50.4
Quadratic Coefficient	[N]	4.53
Maximum Speed	[km/h]	70
Maximum Acceleration	[m/s^2]	1.1
Maximum Deceleration	[m/s^2]	1.1
Minimum Voltage	[Vdc]	500
Rated Voltage	[Vdc]	750
Maximum Voltage	[Vdc]	900
Auxiliary Loads	[W]	106000
Maximum Traction Effort	[N]	144840
Maximum Traction Current	[A]	1587

The traction effort limitation curve can be seen in figure 4.2.

Table 4.4: Traction Effort

Speed [km/h]	Traction Effort [N]
0	144840
6	144840
7	144840
25	144840
44	144840
45	140000
48	132200
50	125000
56	112000
60	105000
64	98000
70	90000

The table 4.5 shows in detail, the considered operation conditions.

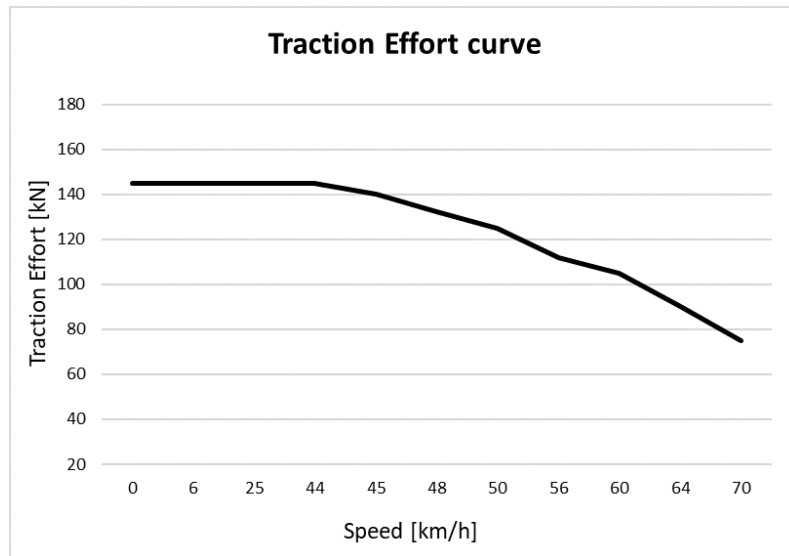


Figure 4.2: Traction Effort limitation curve from the vehicle

Table 4.5: Operation modes input data

Dwell time (seconds)	30
Headway (minutes)	15
Number of trains per hour	4
Number of Operations per day	64
Operation Time (h/day)	16
Number of Operations per year	26280
Operation Time (h/year)	5840

Regarding the operation, was inserted a headway of 15 minutes, which corresponds at four operations (trips) per hour. During a year the number of vehicles that ran on the route was 26280.

Since it is inserted the length of the operation route (d), in this case, 5.3 km, the algorithm calculates nine potential solutions regarding the substation TPS2 position to be located : *TPS2 location*. The values are presented in table 4.6.

Location TPS2	%d	Position in track (m)
Loc1	10	530
Loc2	20	1060
Loc3	30	1590
Loc4	40	2120
Loc5	50	2650
Loc6	60	3180
Loc7	70	3710
Loc8	80	4240
Loc9	90	4770

Table 4.6: Potential locations for substation TPS2 according the lenght of the route

4.1.2 Results from the simulation

In this section are presented the results of the simulation.

This simulation includes the respective input data mentioned in section 4.1.1.

In figure 4.3, is shown the speed performed by the vehicle during the operation. The operation presents different stages related to the speed profile: acceleration, braking, coasting and stopped.

It is possible to see that the route has six passenger stations. The vehicle stops there and starts again after 30 seconds (dwell time).

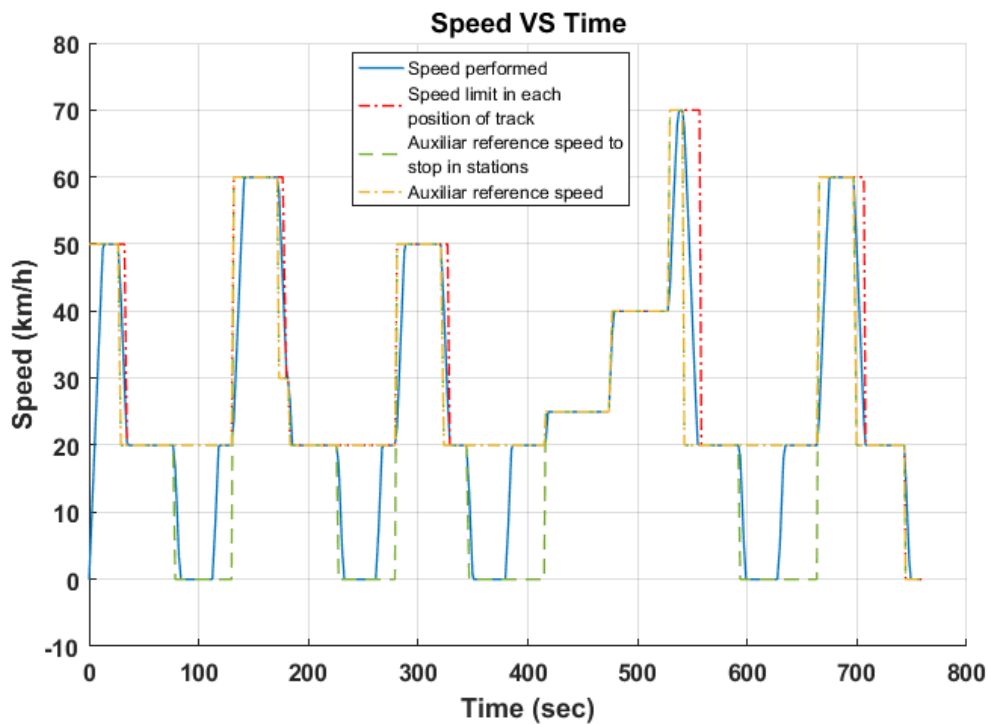


Figure 4.3: Speed limits and Speed performed by the vehicle

The previous figures shows that the vehicle takes approximately 760 seconds (12 minutes and 40 seconds) to travel all the 5300 meters route.

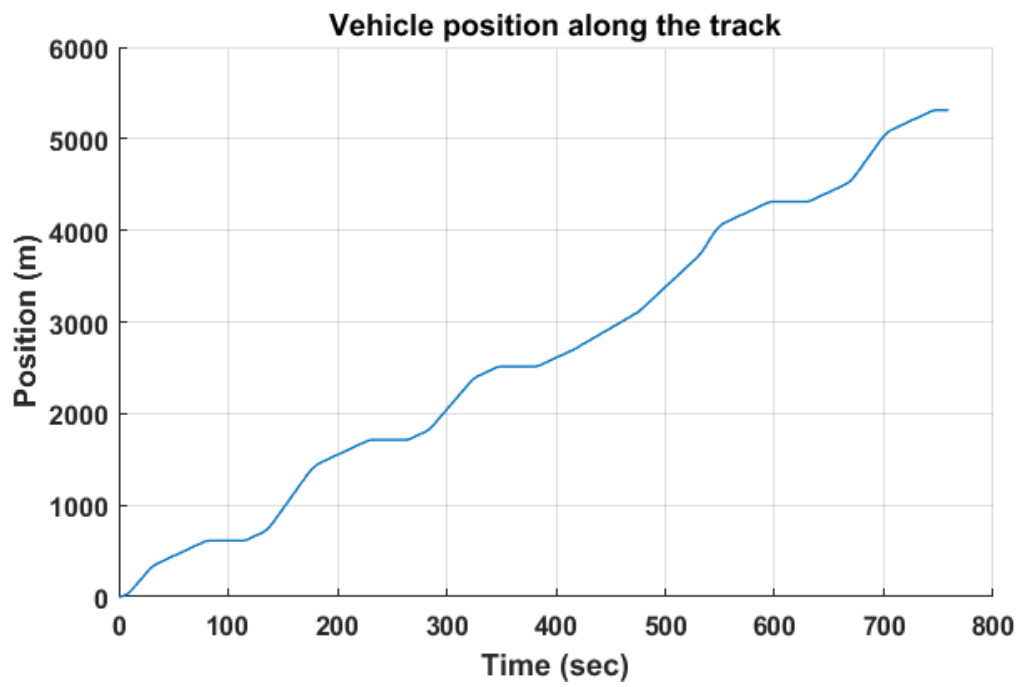


Figure 4.4: Position performed by the vehicle

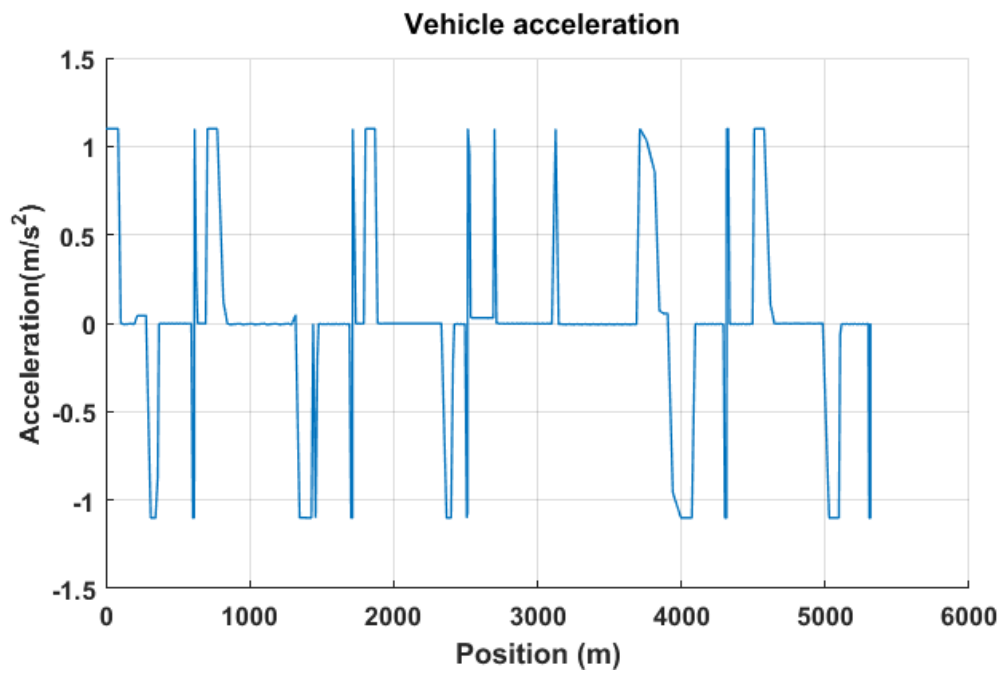


Figure 4.5: Acceleration performed by the vehicle

In figures 4.6 and 4.7 are respectively shown the electrical power and current, required by the vehicle during the operation used to feed traction motors and auxiliary services. It can be seen the limitation at 1585 A, which means the current is dissipated if it exceeds this value.

It can be seen that when the vehicle is in acceleration/traction mode, the power presents positive values and when is braking/deceleration are negatives. The figure 4.7 also shows that when the vehicle is stopped in a station, it is consuming electricity. It occurs because the auxiliary services are activated and consuming.

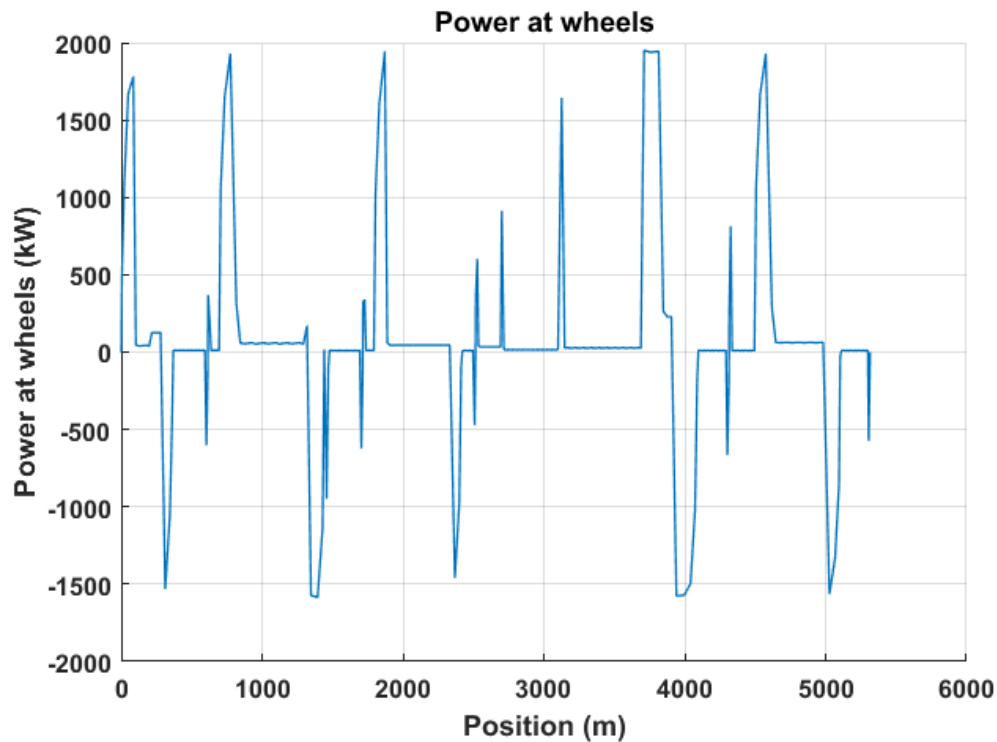


Figure 4.6: Power required by the vehicle along the track

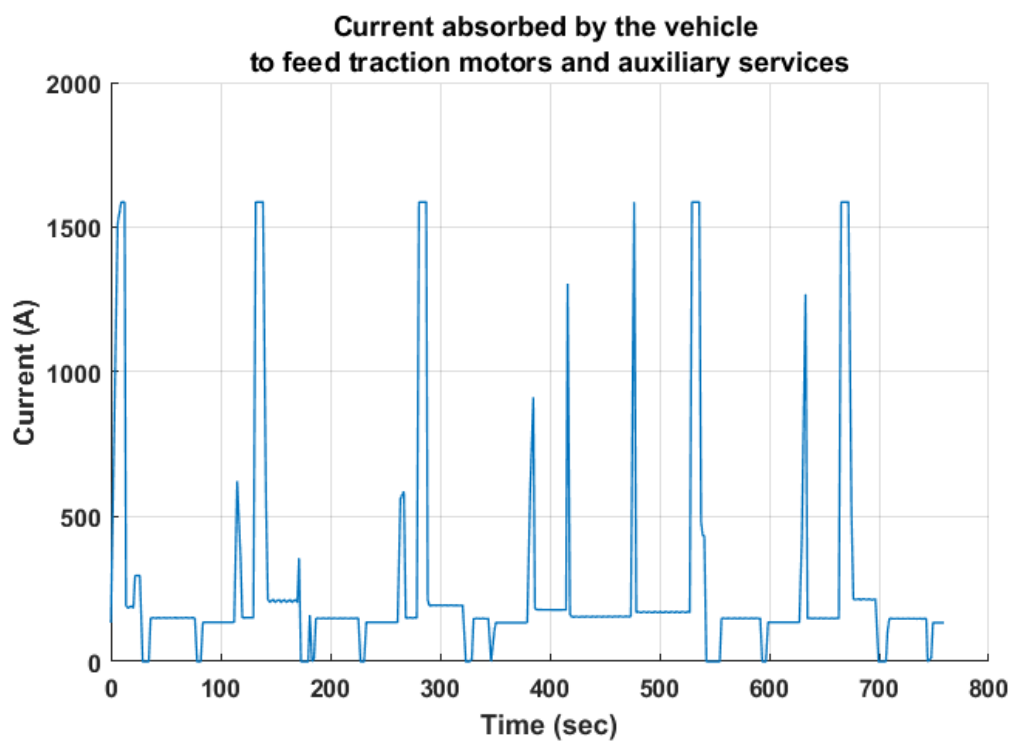


Figure 4.7: Current required by the vehicle used to feed traction motors and auxiliary services

4.1.3 Case Study 1: [PFC120]

In this section is shown the results from a simulation, using a 120sq. mm feeder cable (coded as PFC120). And TPS2 location is varied, in three situations. This method allows to understand the impact on the supply system.

In table 4.7 is possible to see the configurations studied in this case study 1.

Table 4.7: Configuration considered in the Case Study 1

Sudy Case 1		
PF. cable Code (S=120 [sq. mm])	TPS2 Location Code	Respective Position in the route[m]
PFC120	LOC3	1590
PFC120	LOC4	2120
PFC120	LOC8	4240

The drop voltage in contact line, along the route, is shown in figure ??, as is shown the minimal admissible voltage, 500V.

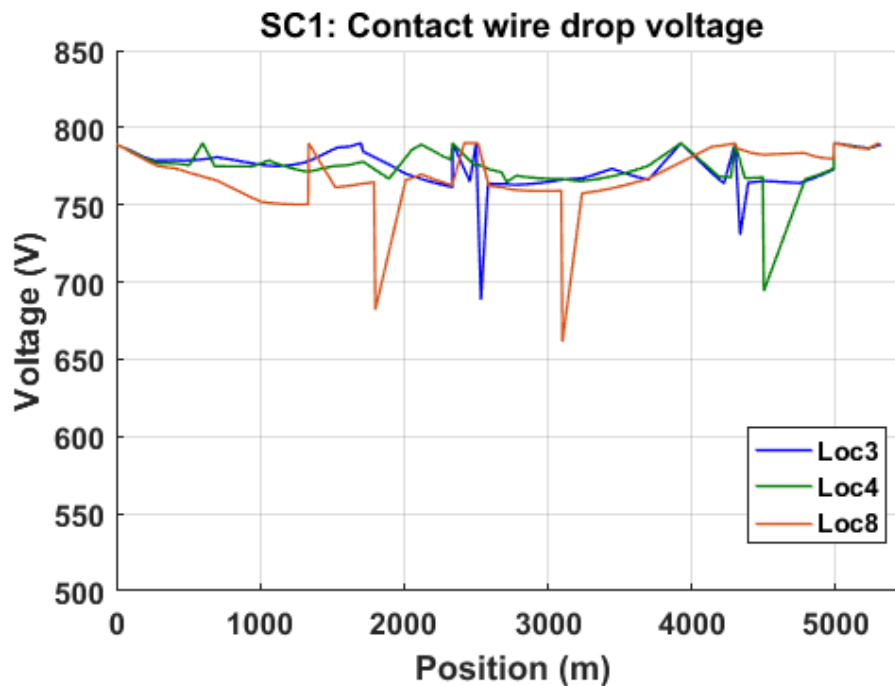


Figure 4.8: Impact of the variation of TPS2 on the drop voltage in contact line

Is possible to see, all the signals are above of 500 V, it means the configurations used in the study case 1, comply with the electrical requirements, regarding the minimum admissible line voltage. Although it is possible to conclude that, with the third configuration, locating the substation TPS2 in LOC8, creates higher drop voltages, getting close to 500V.

It is possible to conclude that the TPS2 location influences the line voltage. For example, when TPS2 is located near TPS1, the length of electrical section from TPS2 to TPS3 increases, increasing the resistance, so, the drop voltage reaches higher values (black line) in this electrical section.

The following figures shows the distribution Power Diagrams from each substation, TPS1, TPS2 and TPS3. These diagrams are valid for both case studies, because the operation is the same.

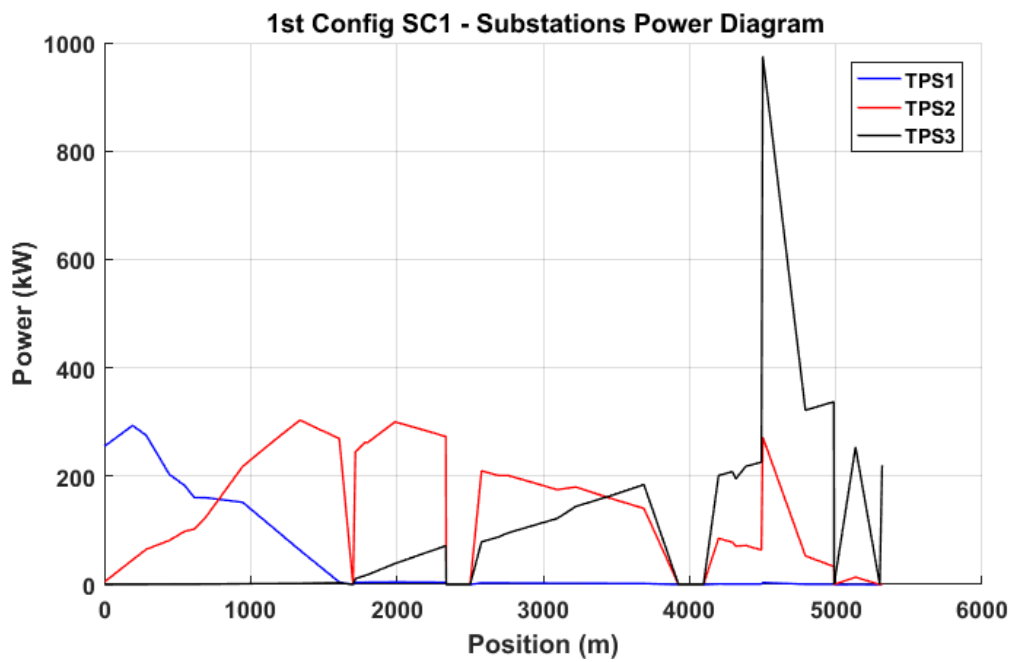


Figure 4.9: SC1: Substations Power Diagram locating TPS2 at 30% of the route

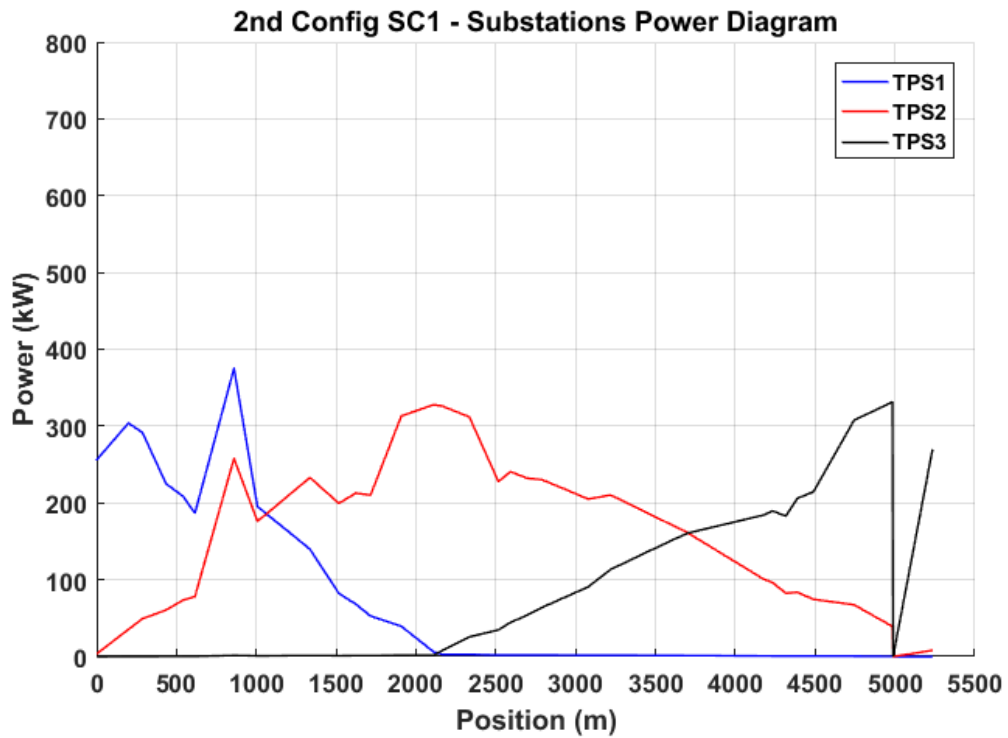


Figure 4.10: SC1: Substations Power Diagram locating TPS2 at 40% of the route

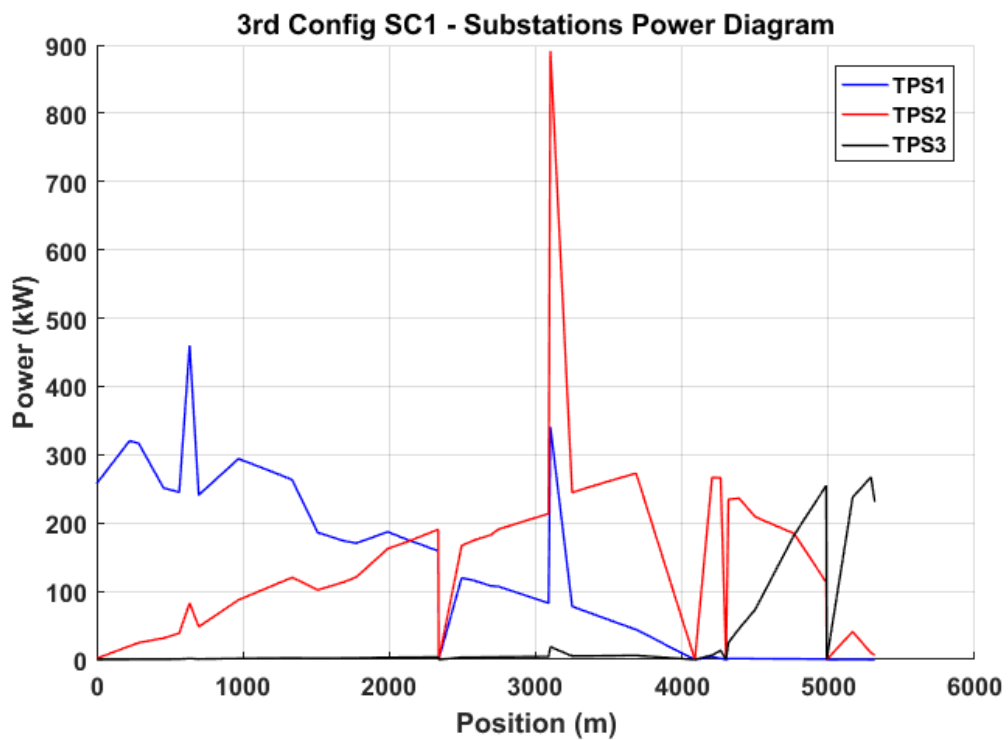


Figure 4.11: SC1: Substations Power Diagram locating TPS2 at 80% of the route

As can be seen, with longer distances between TPS2 and TPS1, the third situation referenced by the code *LOC8*, when TPS2 are located more closed at TPS3, TPS1 will provide more power. In second situation, *LOC4*, TPS2 is located at half way distance, will cause a smooth energy flow from all the substations. When TPS2 is closer to TPS3, a lower consumption from TPS3 is shown, nevertheless, when TPS2 is far from TPS3, the opposite result occurs.

In table 4.8, can be seen the energy consumption values from each substation working for the operation. These values were achieved with the previous mentioned considerations and assumptions.

Table 4.8: Individual and total energy consumption for each configuration

Loc TPS2	Consump TPS1 (kWh)	Consump TPS2 (kWh)	Consump TPS3 (kWh)
Loc3	3.7257	15.8773	8.1098
Loc4	4.8049	11.8388	7.7626
Loc8	11.4006	11.7558	3.0423

In figures 4.12, 4.13 and 4.14, is possible to see graphically the energy consumption evolution for each TPS for each configuration regarding the substation TPS2 location in railway.

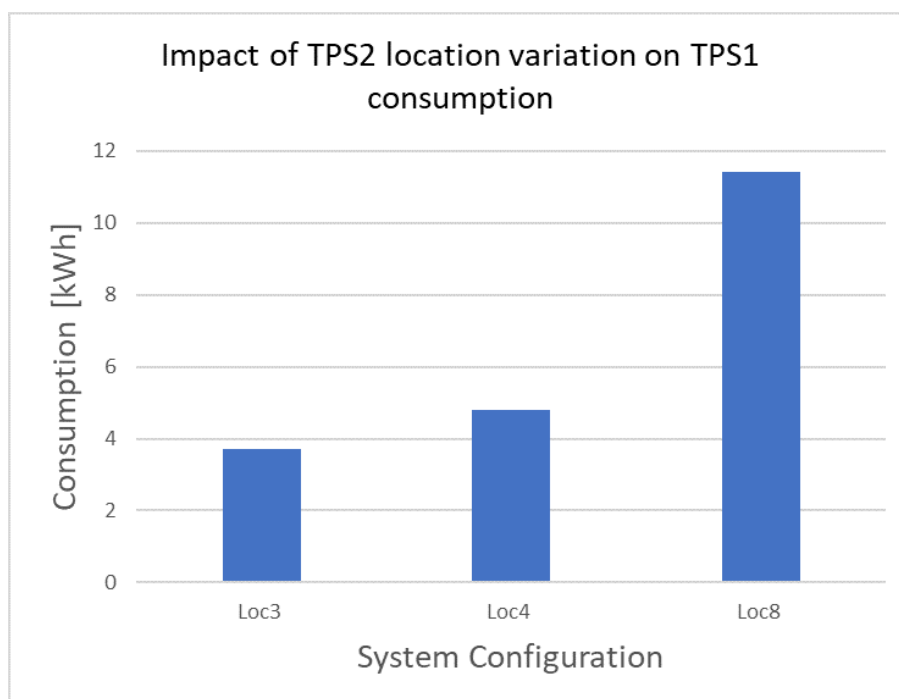


Figure 4.12: Energy consumption by TPS1 along the track

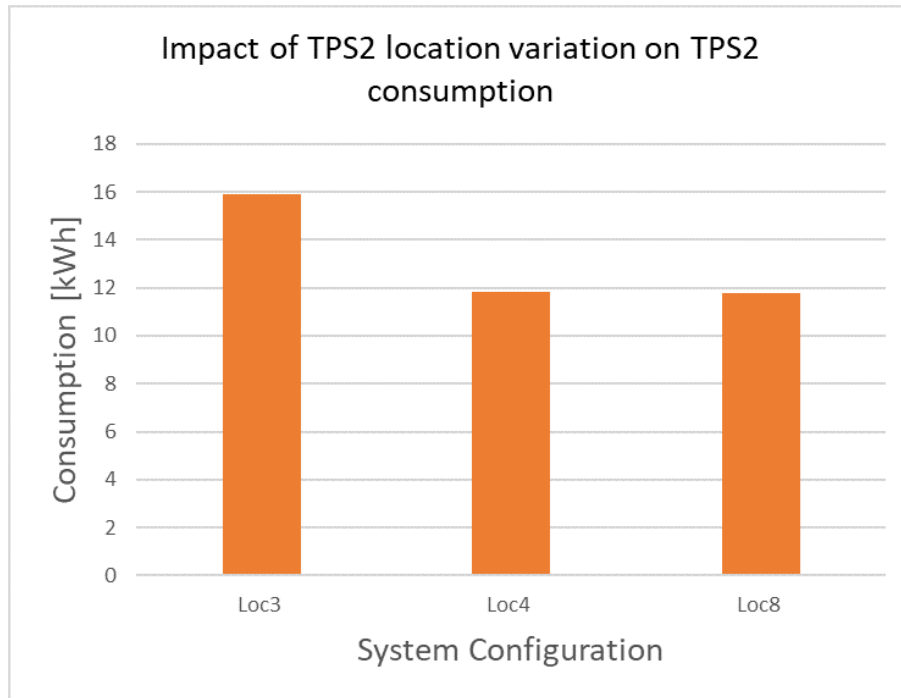


Figure 4.13: Energy consumption by TPS2 along the track

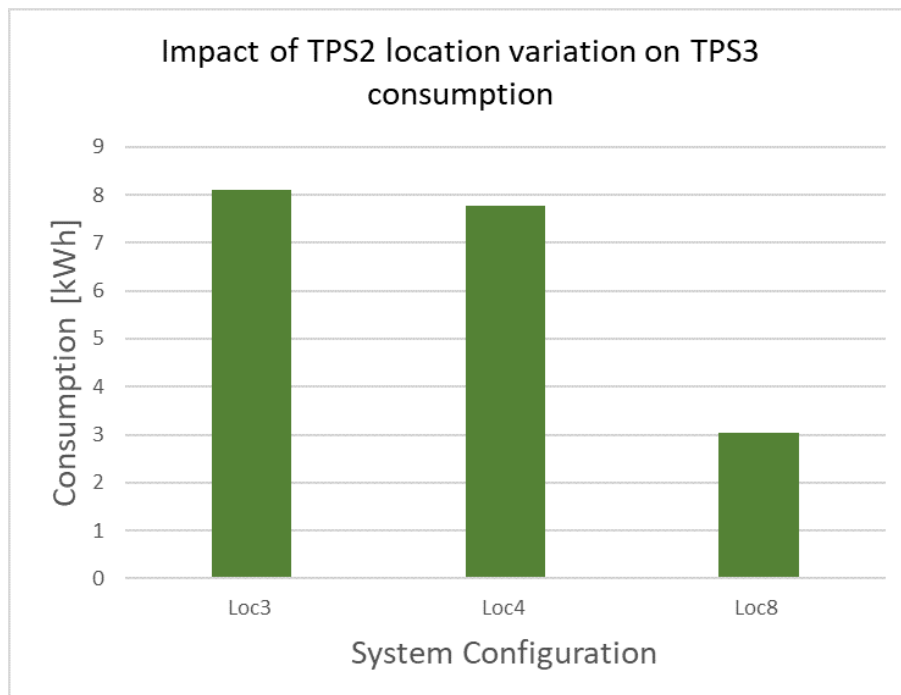


Figure 4.14: Energy consumption by TPS3 along the track

From previous figures, is possible to conclude that when a substation is located far from other consecutive substation, it forces an increase in consumption, in order to ensure the power requirement from operation.

In the following figures can be seen the current delivered by substations, for each configuration.

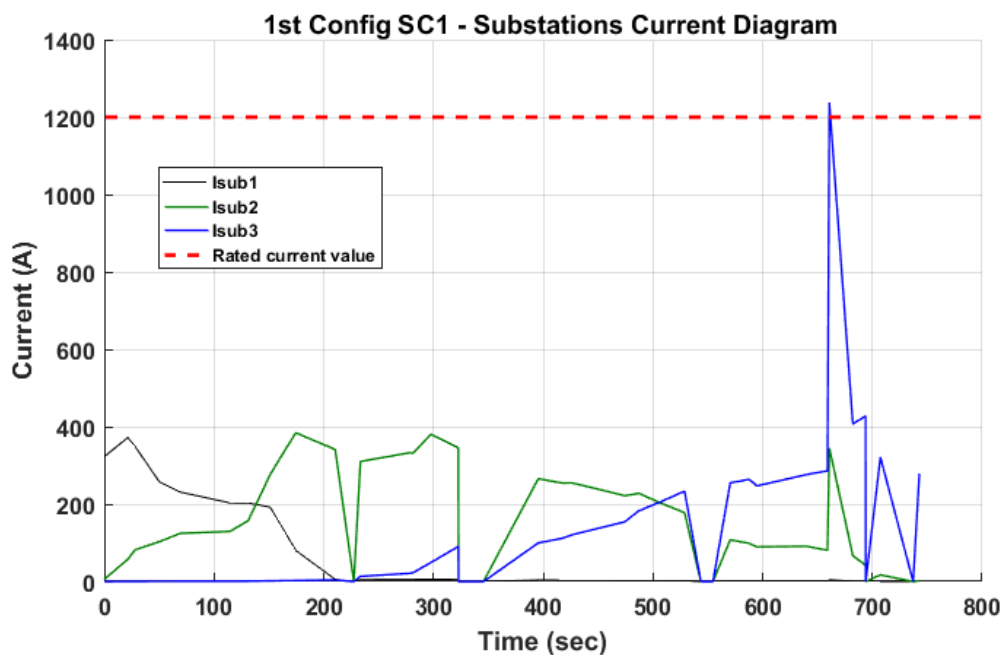


Figure 4.15: Current delivered by substations using a 120sq. mm cable as feeder cable and locating TPS2 at 30% of the route

As is possible to see, from figures above, the configurations in analysis are able to support the operation with no overload. This can be concluded, because the current values are below the maximum admissible.

Using these electrical outputs from substations, it becomes possible to size the traction groups. In this case, as referred in table 3.3, it is possible to equip the substation with only one traction group, being one 1000 kVA rectifier and one 1000 kVA traction transformer.

In table 4.9, is shown the losses from the catenary, for one operation, for the life time period and the respective estimated cost.

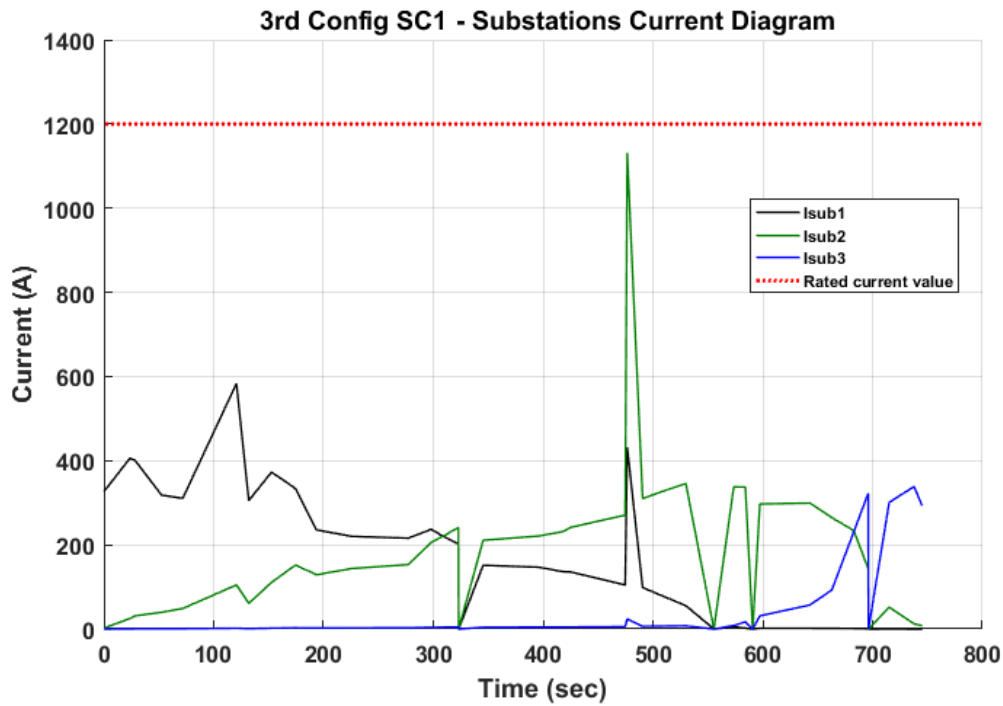


Figure 4.16: Current delivered by substations using a 120sq. mm cable as feeder cable and locating TPS2 at 80% of the route

Table 4.9: Estimated Catenary losses and respective cost

Configuration Code Id	Estimated Losses (1 operation) [kWh]	Estimated Losses (25 years) [kWh]	Estimated Cost Losses [k€/25 years]
(LOC3;PFC120)	0.7282	478434	49.757
(LOC4;PFC120)	0.6595	433192	45.052
(LOC8;PFC120)	1.0223	671653	69.852

The next figures shows the losses by catenary system produced using the configurations from this first study case.

As can be seen, from the previous results, the solution that produces lower losses is the second situation, locating the substation TPS2 at 40% of the route and using 120sq mm cable as parallel feeder cable.

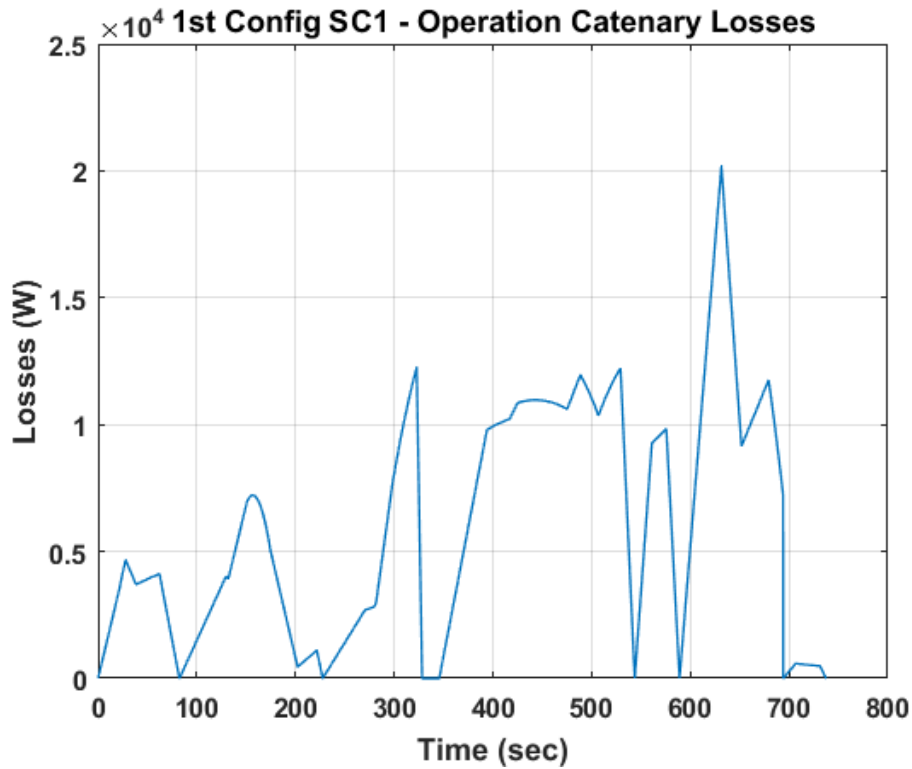


Figure 4.17: Catenary losses using a 120sq. mm cable as feeder cable and locating TPS2 at 30% of the route

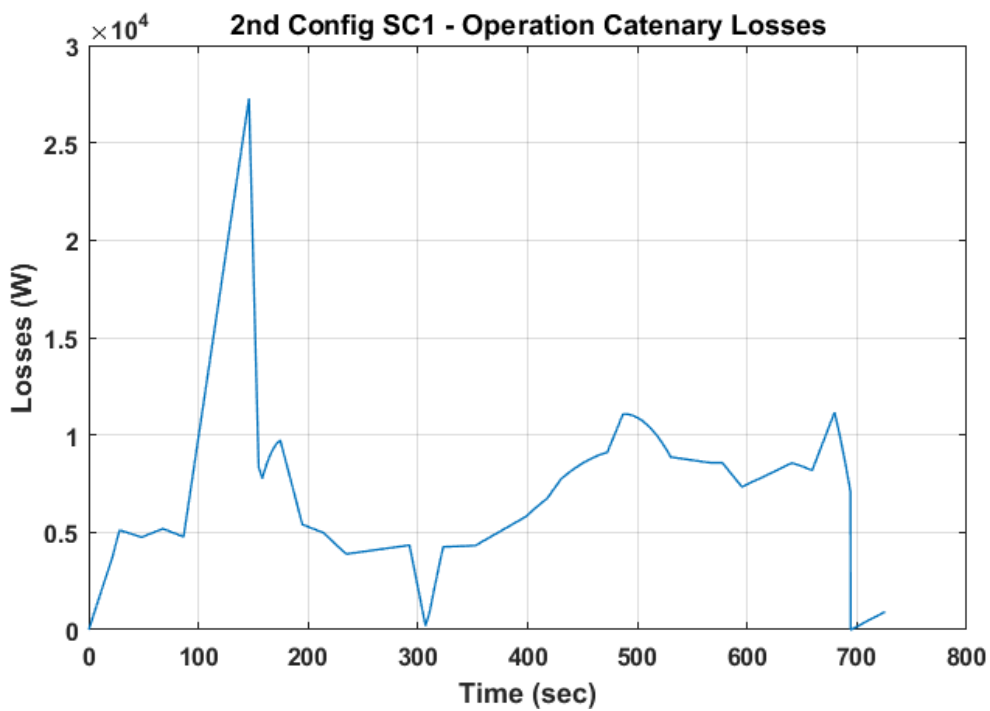


Figure 4.18: Catenary losses using a 120sq. mm cable as feeder cable and locating TPS2 at 40% of the route

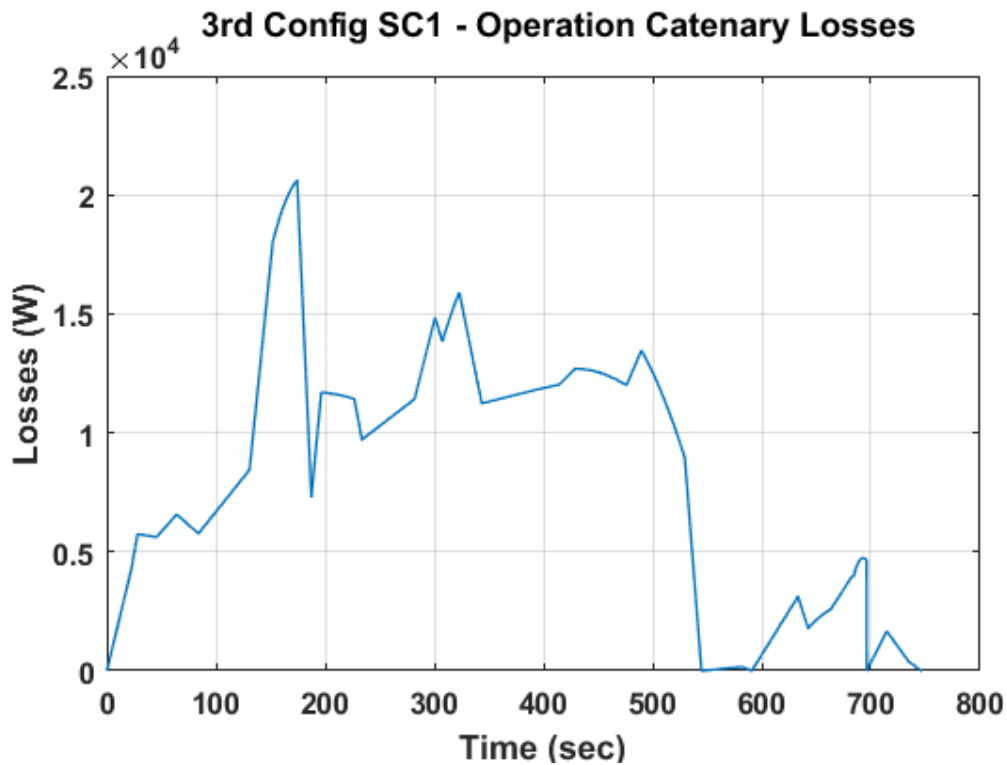


Figure 4.19: Catenary losses using a 120sq. mm cable as feeder cable and locating TPS2 at 80% of the route

To size correctly the system and achieve the best configuration, the algorithm verifies if there is overload in contact wire, in order to protect the catenary system. For this reason, in figure 4.20 is shown the current flow in every branch contact wire from the first electrical section. In this case, for the third configuration, as example.

As can be seen, there are two current spikes above of the maximum permanent current value, the first with approximately 20 seconds duration, although, as these current signals are of short duration, they can be disregarded. So, the configuration is automatically validated by the algorithm.

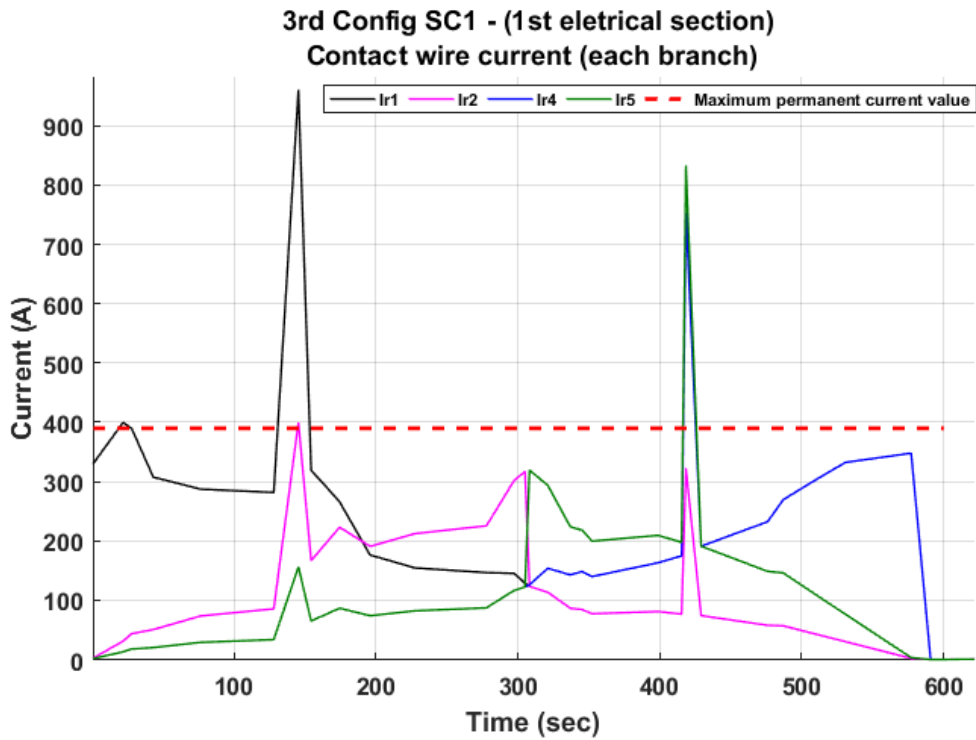


Figure 4.20: SC1: 3rd configuration - First electrical section contact wire current flow

Economically, these configurations show there is high impact on the estimated costs along time. Figure 4.21 shows this evolution, from the start, $t=0$ years, when the traction equipment investment is completely paid.

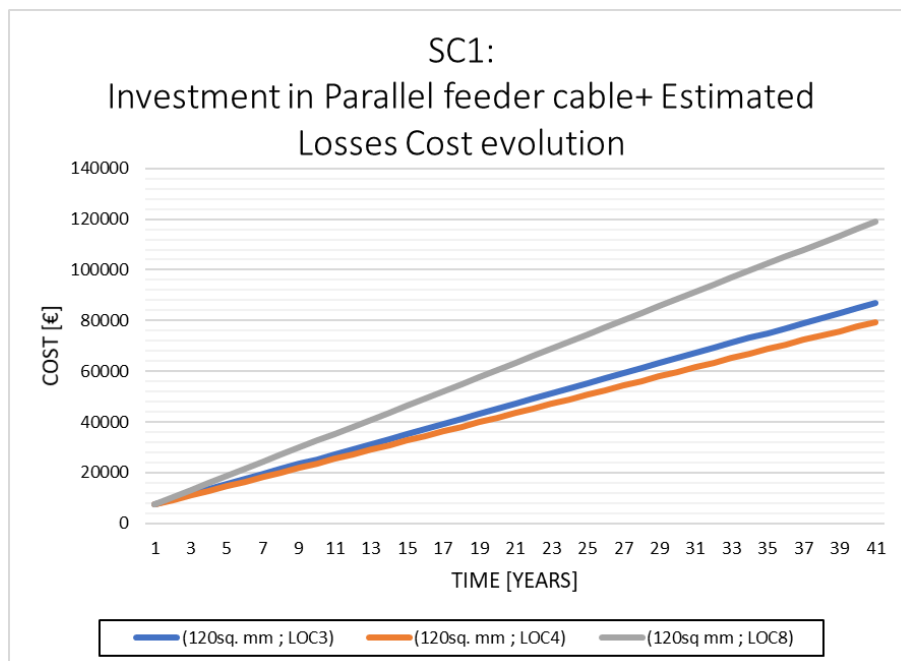


Figure 4.21: Study case 1: Investment cost and estimated losses along the time

Is possible to conclude that the best position to locate the substation TPS2 is in LOC4 at (2120 m of the route). Using these configuration the system can have a potential save of 44.585 k€ comparing with the worst configuration in this study case 1, according the losses and the initial investment.

4.1.4 Case Study 2: [PFC400]

In this section is showed the simulation results, using a 400sq. mm feeder cable (coded as PFC400) and is showed the variation of the TPS2 location impact on the supply system. The same inputs and considerations have been used, because it is intended to compare the results with the first case study and to show the economical balance by using those configurations and comparing both scenarios.

Table 4.10 resumes the configurations used in this second case study.

Table 4.10: Configuration considered in the case study 2

Sudy Case 2		
PF. cable S=400 [sq. mm]	TPS2 Location Code	Position in the route [m]
PFC400	LOC3	1590
PFC400	LOC4	2120
PFC400	LOC8	4240

The drop voltage in contact line, along the route, for the situation, in this case study 2, is shown in figure 4.22, as is shown the minimal admissible voltage, 500V.

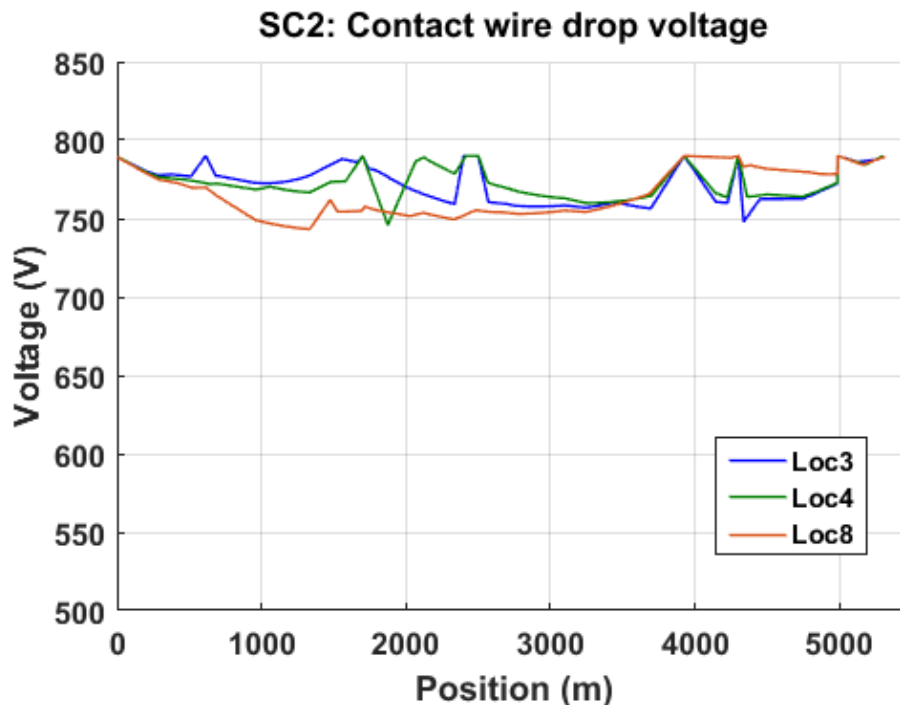


Figure 4.22: SC2: Impact of the variation of TPS2 on the drop voltage in contact line

It is possible to see the configuration from second case study also complies with the electrical requirements, regarding the minimum line voltage, 500V. The figure 4.22 shows lower values of drop voltage. It occurs because, using a parallel feeder cable with higher

section, the resistance becomes lower, so it is generated contact wire drop voltage lower values.

In table 4.11 can be seen the substations consumption results from configurations from this case study 2.

Table 4.11: Individual and total energy consumption for each configuration

Loc TPS2	Consump TPS1 (kWh)	Consump TPS2 (kWh)	Consump TPS3 (kWh)
Loc3	2.805	15.051	7.392
Loc4	1.499	13.265	13.434
Loc8	12.676	12.993	3.462

Table 4.12: Catenary Losses and respective estimated cost for 25 years of operation

Configuration Code Id	Estimated Losses (1 operation) [kWh]	Estimated Losses (25 years) [kWh]	Estimated Cost Losses [k€/25 years]
(LOC3;PFC400)	0.631	414256	43.025
(LOC4;PFC400)	0.570	374403	38.937
(LOC8;PFC400)	0.859	564858	58.745

The follow figures can be seen the current delivered by substations, for each configuration.

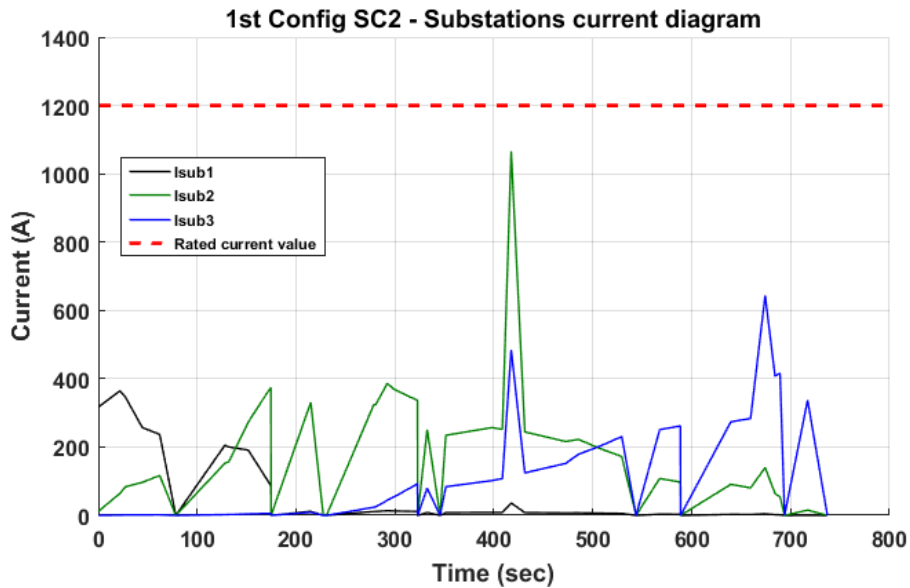


Figure 4.23: Current delivered by substations using 400sq. mm cable as feeder cable and locating TPS2 at 30% of the route

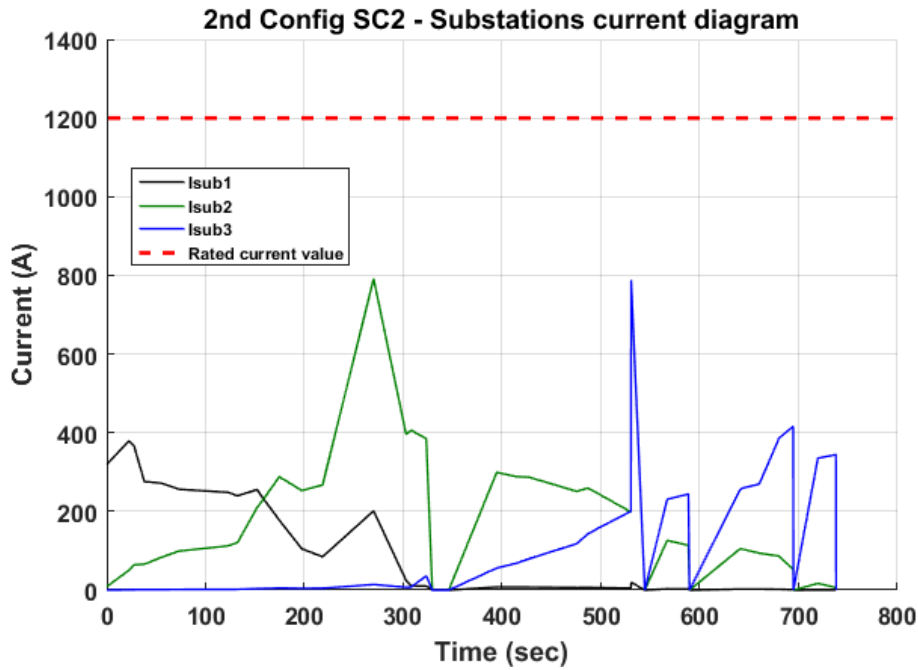


Figure 4.24: Current delivered by substations using 400sq. mm cable as feeder cable and locating TPS2 at 40% of the route

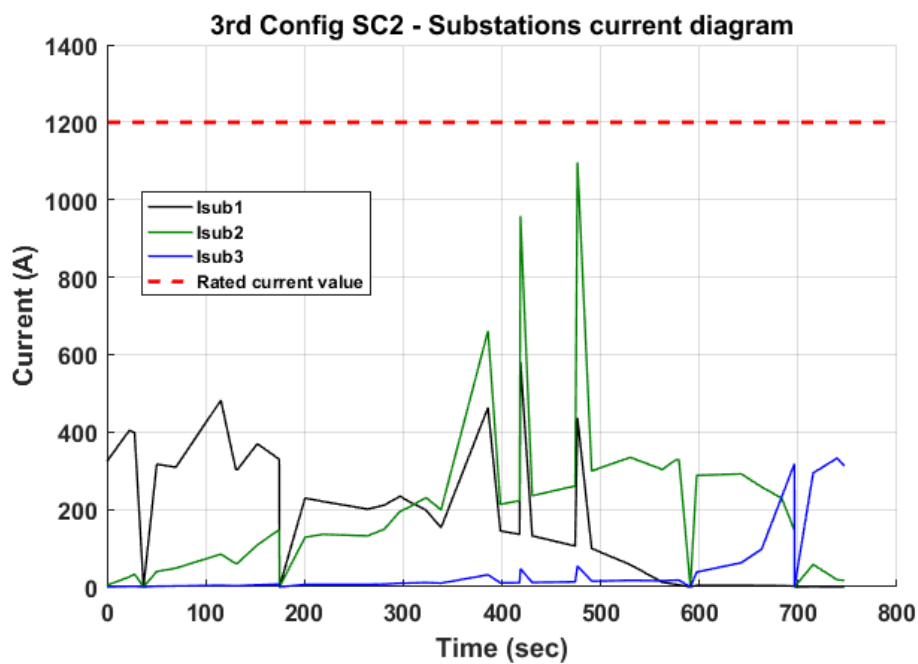


Figure 4.25: Current delivered by substations using 400sq. mm cable as feeder cable and locating TPS2 at 80% of the route

It is possible to see, in previous figure, that using feeder cable with higher section, allows for the decrease of the current flow through contact wire.

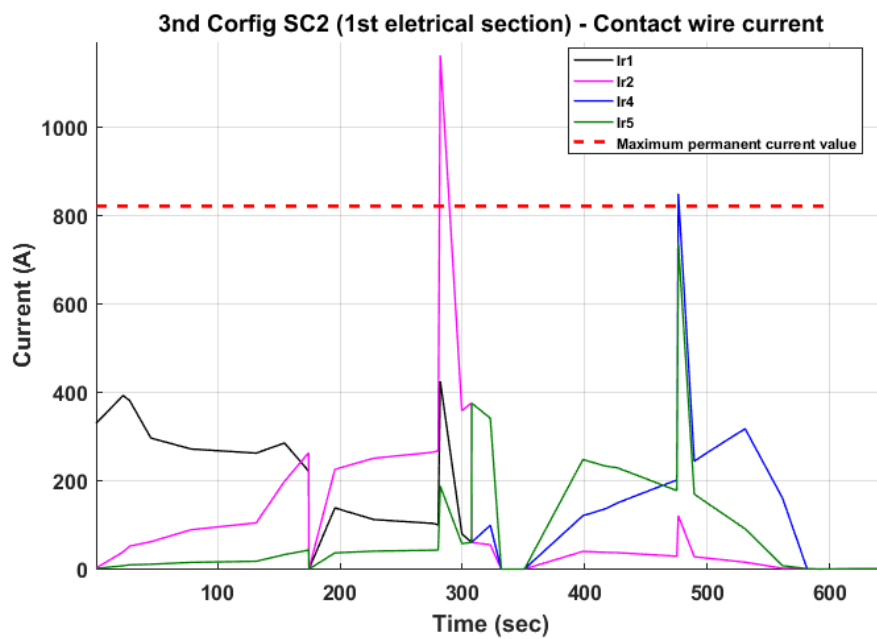


Figure 4.26: SC1: 3rd configuration - First electrical section contact wire current flow

Figure 4.27 shows that using the second configuration: locating the substation TPS2 at LOC4, that is at 2120 meters in the route, the system is able to a potential saving of around 19 k€ relatively the worst configuration in this study case.

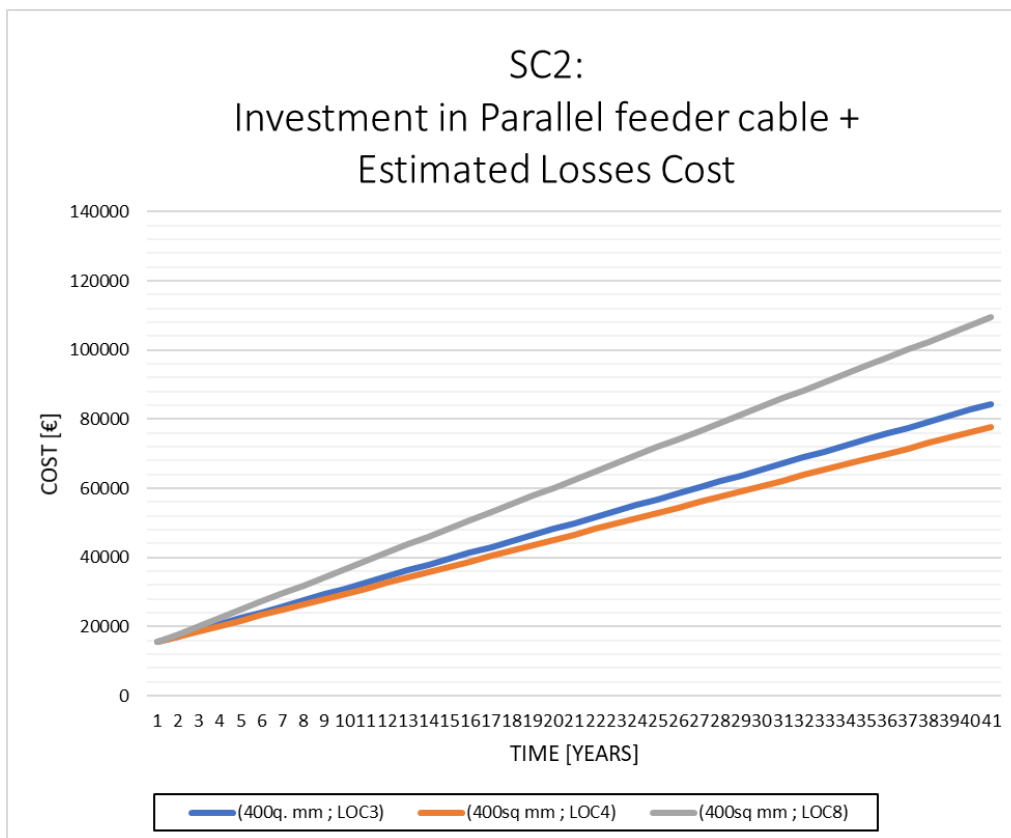


Figure 4.27: Study case 2: Investment in cable and estimated losses cost along 25 years of operation

4.1.5 Case Study comparative analysis

In order to compare both scenarios and verify the impact of using different systems configurations on estimated losses, it is shown a bar chart in figure 4.28. The light colours represent the SC1 values and dark colours the SC2 values.

As is possible to see, varying substation TPS2 location change the estimated losses value. The minimum value is found using the second configuration LOC4, valid in both feeder cables (using SC1 and SC2).

The second conclusion is that using a higher feeder cable section, which is simulated in SC2, the estimated losses values are lower.

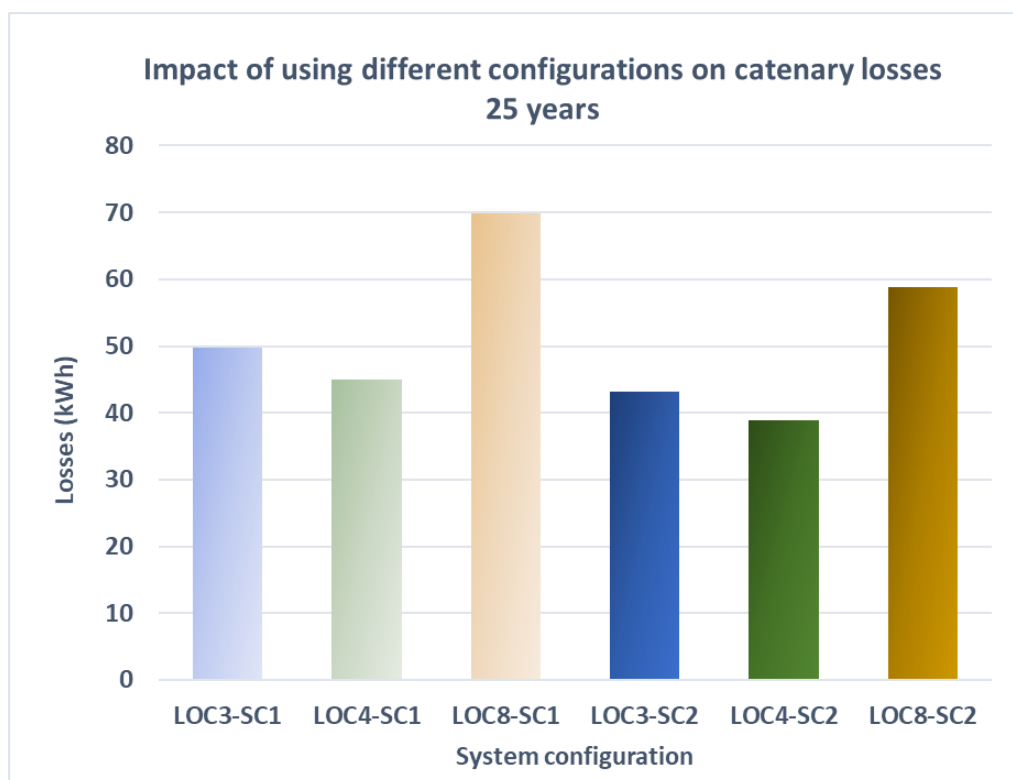


Figure 4.28: Case studies 1 and 2: Impact of using different configurations on catenary losses along 25 years operation

Figure 4.29 shows the estimated losses cost evolution along the years, considering the feeder cable initial investment. Each line represents different traction system configurations, using different parallel feeder cables in catenary and varying the substation TPS2 location.

As can be seen, comparing the lines, the relative best system configuration is represented by the orange line, that shows lower value after the considered life time, 25 years.

It is also possible to see that in situations from the second study case, represented by green and yellow lines, in spite of a higher initial investment, after a time, those configurations presents lower values comparatively to solutions with 120sq. mm. For example, after 9 years, those lines are lower comparing to the gray line and after 19 years, the green

line crosses the dark blue line, which means, after 19 years, theoretically, this solution will be inexpensive and more environmentally friendly.

Other conclusion, is if will be used a configuration represented by the green line, after 34 years, these system becomes the inexpensive solution. Although, is a long time to be considered in this dissertation.

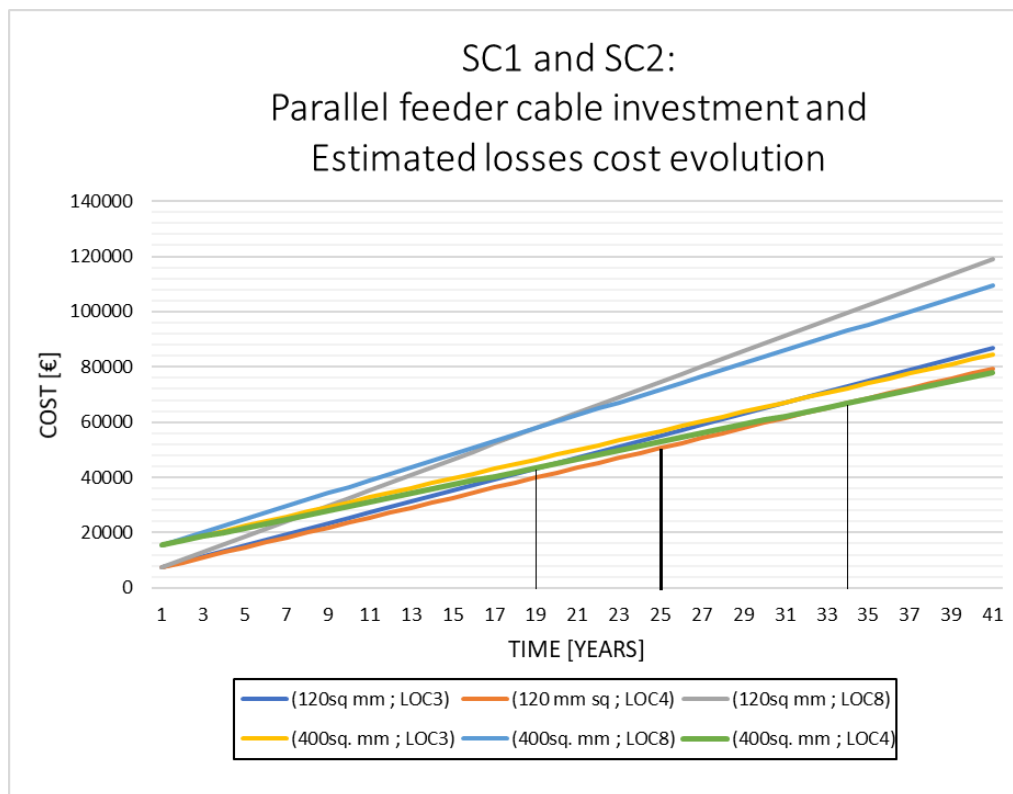


Figure 4.29: Study case 1 and 2: Investment cost, estimation losses cost and the relative best solution

In table 4.13 can be seen the relative best solution detailed costs.

Table 4.13: Best relative solution detailed cost

Solution [LOC4,PFC120]		
Parameter	Estimated Cost	Total
Losses	45053 €	52473€
Investment Cable PFC120	7420 €	

4.1.6 Cost estimation using Matrix Method - Global Finder Simulation

In this section is presented the overall best solution and are showed two methods to find it, using the *Matrix* and *GA* Methods.

The first method, makes use of an extensive search from the overall of 72 "possible"solutions and the second use genetic algorithms to search the solution. Both methods have the final purpose to find the minimum final cost value, for the system to take into account losses minimization.

Then is showed the optimal solution, the respective electromechanical results and is presented an economical evolution, for the life time 25 years. It is intended to find the best investment cost for this period and the potential savings relatively to using other system configurations.

The Matrix method results can be seen in a 2D matrix, resulted from equation 4.1. The estimated system cost from each configuration is represented by each position (row,column) from the matrix.

So, 8 rows corresponds to the 8 possible auxiliary feeder cables and 9 columns corresponds to 9 possible locations for TPS2. The optimal configuration, corresponds to the minimum value of the matrix.

$$Costs = \begin{bmatrix} 167201 & 87001 & 82191 & 88511 & 92671 & 75031 & 90661 & 141751 & 109591 \\ 78315 & 48802 & 70338 & 52473 & 71102 & 69391 & 85946 & 81722 & 139762 \\ 56666 & 102011 & 60249 & 43023 & 56927 & 60301 & 92349 & 63370 & 105186 \\ 82007 & 66661 & 66181 & \mathbf{42475} & 66756 & 60285 & 53356 & 103278 & 115639 \\ 121044 & 81527 & 78601 & 44146 & 50241 & 66909 & 104558 & 129212 & 112877 \\ 100758 & 85955 & 69440 & 62788 & 63993 & 69697 & 66685 & 67235 & 85139 \\ 107724 & 70104 & 67979 & 50223 & 57776 & 68611 & 83696 & 74819 & 66593 \\ 143052 & 79966 & 71091 & 65341 & 80203 & 72293 & 89409 & 106294 & 88477 \end{bmatrix} \quad (4.1)$$

The surface graph represented in figure 4.30 shows the variation impact of the variables on the wasted energy by catenary.

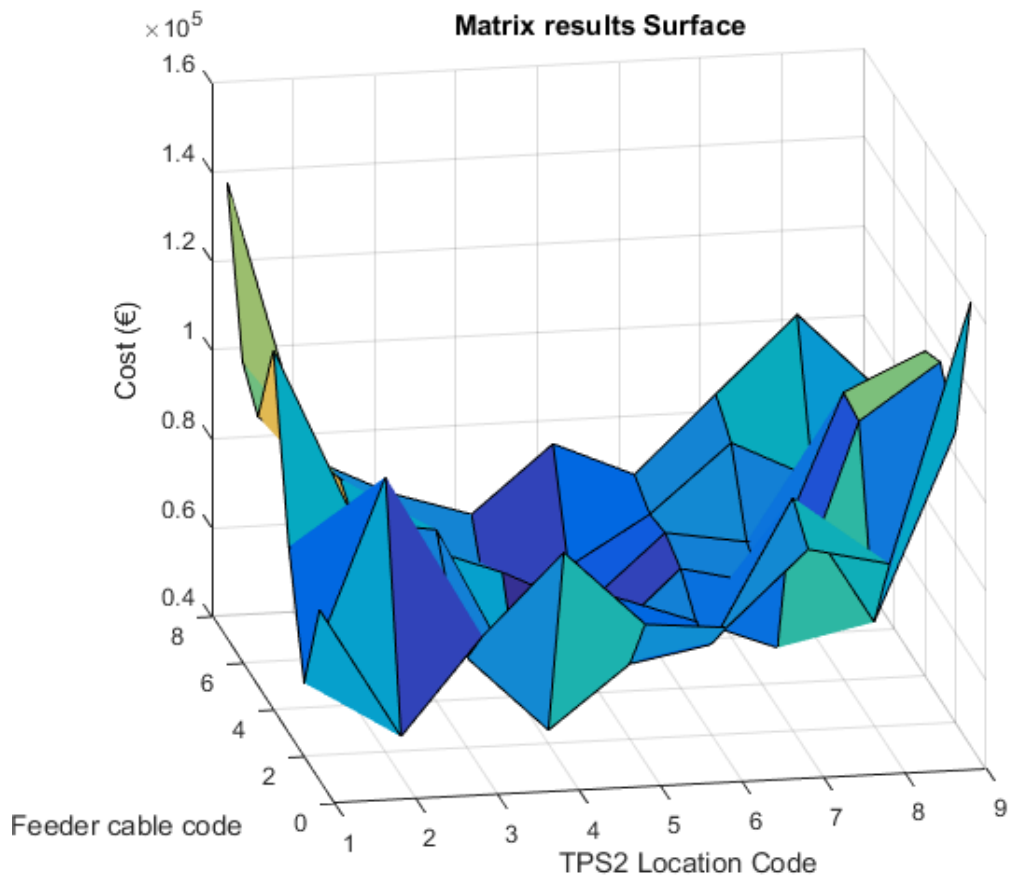


Figure 4.30: Surface graph that shows the impact of the variables variation on the estimated losses

The achieved solution, is presented in table 4.14.

Table 4.14: Best configuration for 25 years operation

PFC	LOC
4	4

It means the optimal solution is locating the substation TPS2 at 2120 m of the route with an investment in a 240sq. mm cable as feeder cable for catenary system. Figures 4.31 and 4.32 respectively show the achieved best configuration and a route map overview with stations and substations

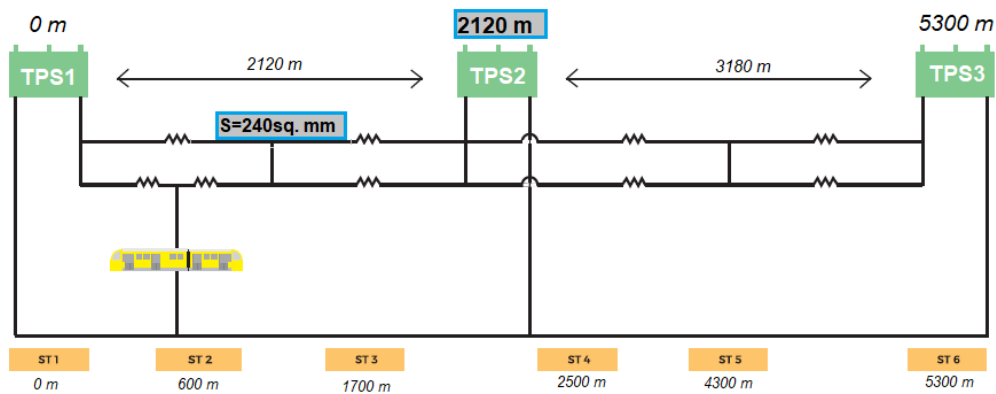


Figure 4.31: Achieved best configuration overview

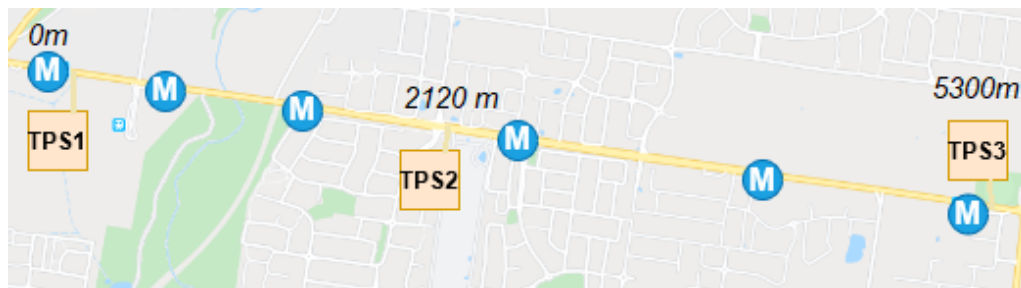


Figure 4.32: Route map overview

The following results are the electrical outputs from the achieved best traction system configuration. As the operation is the same, the mechanical output results previously showed in the case studies are the same.

As it is possible to see, the model complies with the electrical requirements, relatively to the minimum voltage in the contact line, as can be seen the contact wire drop voltage along the line is above the minimum admissible, 500V.

In figure 4.34 is shown the power diagram from each substation using the achieved best configuration.

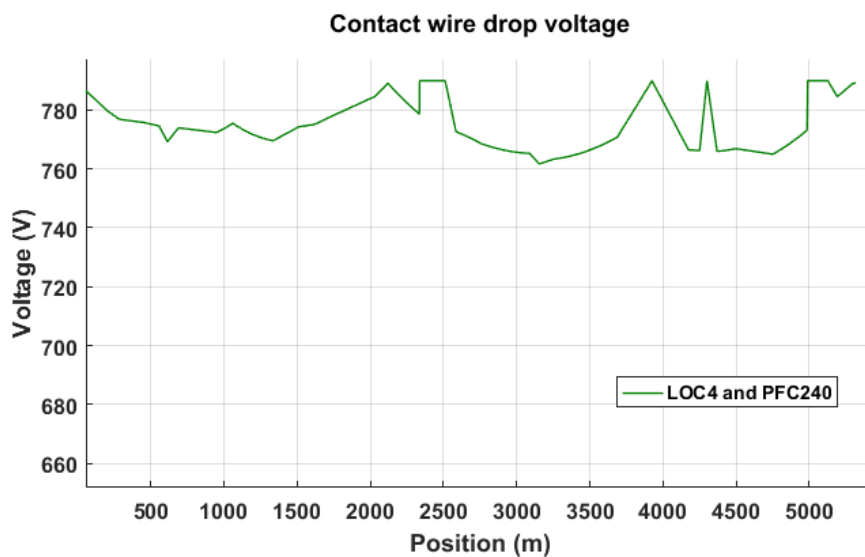


Figure 4.33: Best configuration: Contact wire drop voltage

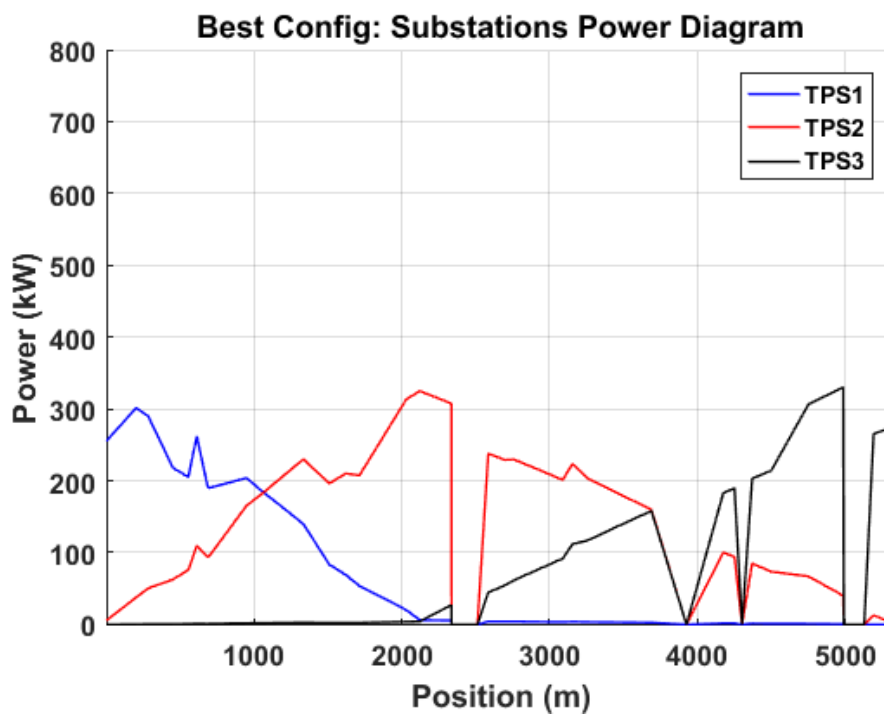


Figure 4.34: Best configuration: Substations Power diagram

In table 4.15 is shown the consumptions from each substation.

Table 4.15: Substations Consumptions

Consump TPS1 [kWh]	Consump TPS2 [kWh]	Consump TPS3 [kWh]
4.0604	10.1765	7.0827

The following figures show the current delivered by substations using the achieved best configuration.

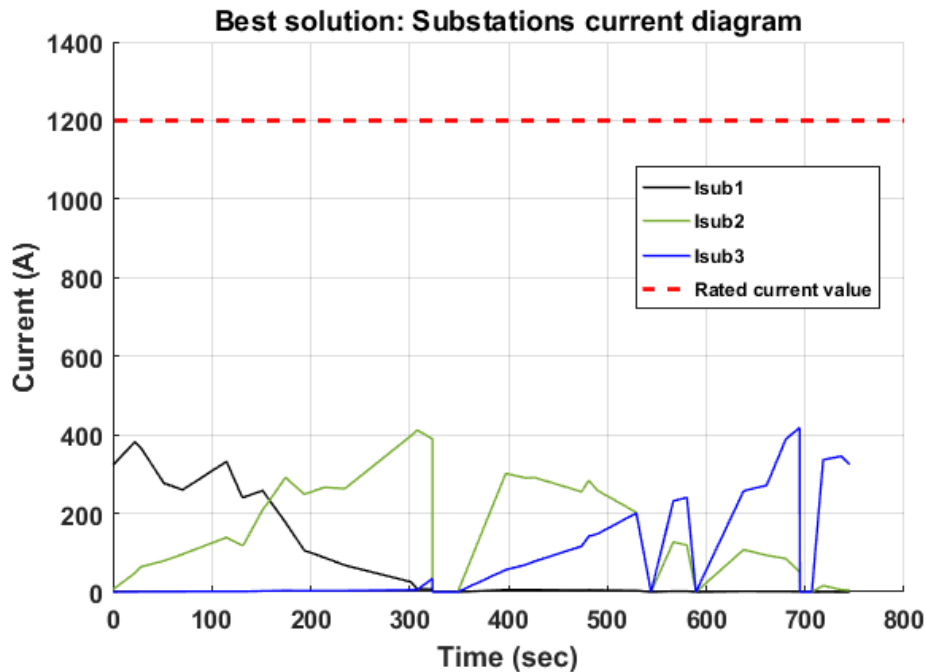


Figure 4.35: Current delivered by substations using 240sq. mm cable as feeder cable and locating TPS2 at 40% of the route.

The algorithm use the previous represented results to size the traction groups from substations. So it is possible to conclude, that one traction group for each substation is enough to support the operation.

In figure 4.36 and in table 4.16, can be seen the results regarding the catenary losses.

The resulted estimated losses and the respective cost for the 25 years of operation are as follows:

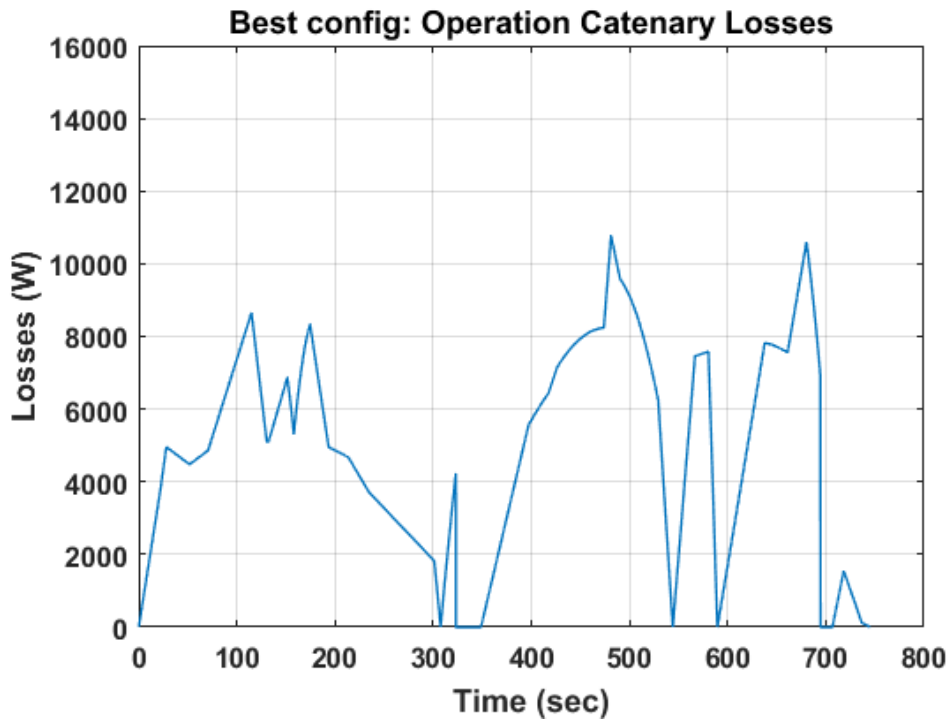


Figure 4.36: Catenary Losses using the achieved best configuration

Table 4.16: Resulted Losses

Average Losses [kW]	Estimated Losses (1 operation) [kWh]	Estimated Losses (25 years) [kWh]	Estimated cost Losses (25 years) [€]
6222	0.405	265726	27635

Since one traction group are sufficient to maintain the operation without any overloads. The cost used in energy equipments for substations are: 1.035 M€, (345 k€ each substation). This value is an estimate value in this dissertation and should not be considered as a reference.

The next result, intends to show the economical evolution using this solution and show the advantages comparing using others configurations. These results were achieved using the same inputs and operation conditions that were used in previous simulations. In figure 4.37 can be seen the estimated cost, used to pay the wasted energy delivered by catenary system, and the initial investment in cable to use as parallel feeder cable.

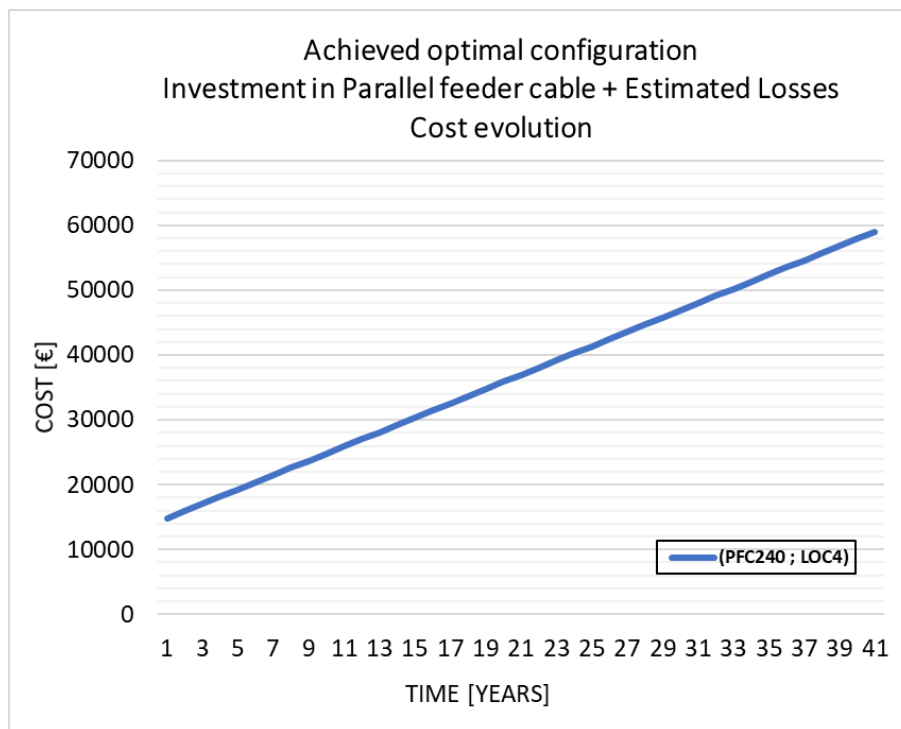


Figure 4.37: Achieved optimal solution estimative cost evolution: Investment feeder cable and catenary losses

The figure 4.38 shows the difference to use the achieved optimal configuration relatively others, during the life time period. The lines represents the different configurations cost evolution, the orange and gray lines are from configurations previously studied in first and second case studies, respectively.

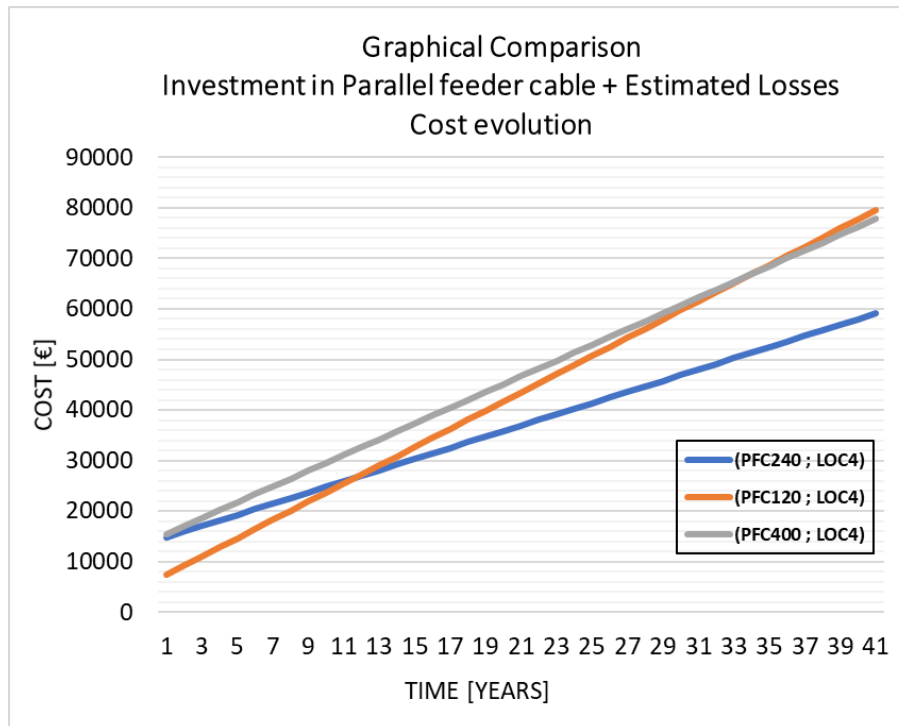


Figure 4.38: Comparison estimative cost evolution: Investment feeder cable and catenary losses

As can be concluded, after approximately 12 years, these solution becomes the more inexpensive solution comparing the others. Is possible to see, that using these solution, in 25 years of operation, can potentially and theoretical be saved approximately 10 k€ and 12k€ comparing the results from the others configurations, in spite of different initial investments.

Finally, the equation used to achieve the final cost for the traction system can be seen as follows:

$$cost = Cost_{TPSs} + Cost_{FeederCable} + Cost_{Losses} + Cost_{Consum} \quad (4.2)$$

In table 4.17 can be seen the final values, considering the consumption costs from the operation and the initial investments in equipments. As is possible to see the total estimated cost in losses represents only approximately 1.9% from the total energy consumption by substations.

Table 4.17: Best configuration parameters final costs

Parameter	Costs [k€]
Investment TPSs	1035.000
Investment Feeder Cable	14.310
Losses	27.635
Consumption	1456.719
Total	2534.194

4.1.7 Cost estimation using GA Method

In this section is presented the GA method, which uses genetic algorithm to solve the problem. Using the same simulation parameters, assumptions and considerations, it has been applied using simulink. The algorithm after 5 generations, finds the best system configuration and returned the minimum estimated cost.

The resulted best solution (optimal configuration), is presented in table 4.18.

Table 4.18: Resulted optimized parameters using the GA method

Loc	PFC
4	4

In figure 4.39 can be seen the convergence solution progress of the algorithm along the "generations". As we can see, the solution was achieved in 5 generations.

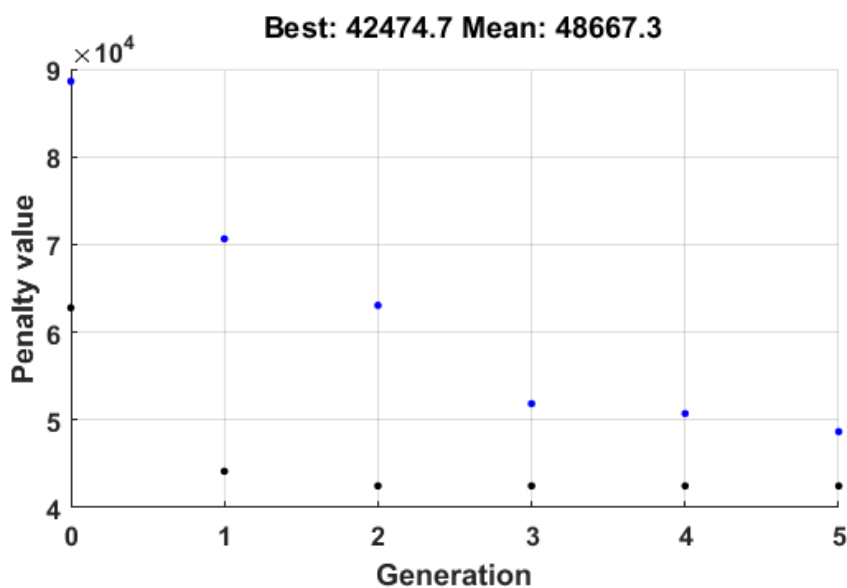


Figure 4.39: The best fitness value vs the number of generations in the GA

Finally, it was achieved the estimated cost in losses and the initial investment in cable to use as parallel feeder cable, that is approximately 42475 €. As the operation is under the same conditions, the equipments and operation consumption are the same.

CONCLUSIONS AND FUTURE WORK

5.1 General Conclusions

In this dissertation has been developed a tool that estimates the minimum cost for a DC traction system with one vehicle operating in a track fed by a traction supply system, considering its life cycle. The study was based in estimated operation consumptions and in the consequently the respective electricity cost, which was pretended to minimize.

It was possible, trough the optimization the system model, precisely, by using the system configuration that generates less losses and by using optimized equipments. The methods used to simulate the system was the substation TPS2 location and the section of the parallel feeder cable from catenary system. Where it was verified that in spite of a higher initial investment in cable, the system generates less losses and potentially become a less costly solution after some time.

It was presented a comparative analysis, comparing the electromechanical results and the economical evolutions from both configurations, considering losses and the feeder cable cost.

GA method showed to be an effective algorithm to find the solution, as it finds the same final solution as the Matrix method, although it doesn't show all the results to be possible compare or to be aware of the overall results.

In resume, the obtained results for the study case were conclusive, the best traction system configuration was found and the respective cost was estimated. Also, it is verified that the system complies with the electrical requirements regarding the minimum drop voltage in line, overloads in traction groups and contact wire.

5.2 Future Work

Being the railway and tramway transportation an area in constant development, due to its relevance in the public sector, it becomes important to increase the investment in study and improving the systems relatively to the power supply. Also it seems important, the investment in tools that help achieve systems best configurations, taking into account losses minimization.

For this reason, it is suggested as future work for this dissertation the following features:

- Develop a user-friendly graphical interface;
- Extend the software, allowing the modelling of longer routes, with more substations and vehicles operating;
- Create a reliability simulation test in case of failure of any substation.
- Improve a method to apply parallel feeder cable only in the critical parts of the line.

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