POLITECNICO DI MILANO

School of Industrial and Information Engineering

Department of Electronics, Information and Bioengineering

Master Degree in Automation and Control Engineering

Efficiency analysis of a railway system: modelling and validation

Supervisor: Prof. Marco Mauri

Master thesis of:
Samuele Moscatelli
Personal code 872112

Academic year 2017/2018

Summary

1 Introduction 1

1.1 Thesis purposes 3

2 Italian rail traction system 4

2.1 Catenary 5

2.1.1 Contact line 5

2.1.2 Protection system 6

2.2 Electrical substation (ESS) 6

2.2.1 Primary lines 7

2.2.2 ESS generalities 8

2.2.3 Switches and disconnectors 8

2.2.4 Power transformers 9

2.2.5 Rectifier 10

2.2.6 Output filter 12

2.2.7 Extra-rapid switch 13

2.2.8 Surge protection devices 13

2.2.9 Mobile substation (MSS) 14

2.3 Train 14

2.3.1 Mechanical system 14

2.3.2 Force analysis 18

2.3.3 Train motor 21

2.3.4 Transmission 23

2.3.5 Auxiliaries 24

2.3.6 Measurement instruments 24

2.3.7 ETR 500 26

2.4 AC lines 27

2.4.1 Line components 29

2.4.2 Electric Substation 30

2.4.3 Double Parallel Place 30

2.4.4 Neutral Section 30

2.4.5 Catenary 31

2.4.6 Protections 32

3 System modelling 33

3.1 System components 33

3.1.1 Electrical substation (ESS) 34

3.1.2 Catenary 38

3.1.3 Train 39

3.2 Evaluation of system power block 41

3.2.1 Traction power 42

3.2.2 Friction power losses 43

3.2.3 Declivity power 44

3.2.4 Curvature power losses 44

3.2.5 Auxiliary power 45

3.2.6 Efficiency box 46

3.3 Train position 47

3.4 Railway system complete model 47

3.4.1 Case with 1 ESS 48

3.4.2 Case with 2 ESS 49

3.4.3 Manager logic 50

3.5 Model reusability 50

3.5.1 Evaluation of different train configurations 51

3.5.2 Substation and catenary configuration changes *52*

3.5.3 Transition from DC to AC traction.. *54*

4 Recovery strategies **58**

4.1 On-board storage 59

4.2 Electrical substations storage...60

4.3 Reversible substations 61

4.4 Smart grid implementation 64

5 Validation **66**

5.1 Data comparison..66

5.2 Model validation..69

5.2.1 Train position validation.. *69*

5.2.2 Power validation *70*

5.2.3 Voltage validation *72*

5.2.4 Entire model validation.. *74*

6 Simulations...**77**

6.1 Electric substation with battery packs 77

6.2 Simulation with different velocity profile......................................81

6.3 Simulation with different velocity profiles and with battery storage 87

7 Conclusions and future development...**95**

7.1 Outcomes..95

7.2 Future works 97

References **100**

Abstract

The work aim is the definition of a model in Matlab and Simulink environment which could simulate a railway system, in particular for what concerns its electrical variables, in order to have an appropriate instrument for studying and analysing the behaviour of a railway vehicle in nominal functioning conditions, but above all to determine the impact on the railway line which may implement innovative components suitable for the reduction of energetic consumptions and the consequent polluting emissions, in the actual scenario of reduction of environmental impact. One of the key points is to have a model which is as flexible as possible and adaptable to situations different from the ones of initial design, in order to make immediate the implementation of new components.

Therefore, it will be firstly shown the actual state of art of railway technology, with a particular attention to the 3000V DC lines, which is the predominant technology in Italy. Hence it will be analysed its principal components, from the electric substation which power it, to the trains which represent the predominant utilizers, without neglecting the catenary through which all the elements are linked. Moreover, it will be dedicated a short paragraph even to high velocity and high capacity lines, powered by a monophase AC system.

Then it will be described the modelling of the different components which constitute the model itself, with a certain attention at realization hypotheses and justifying them; in a second time it will be exposed some strategies which could reduce the energetic consumptions of the entire infrastructure, acting on the recovery of the energy regenerated by trains during braking and currently underutilized.

Finally, after that the model will have been validated and its results verified, it will be shown some simulations regarding the application of two reduction strategies and the corresponding effects on consumption and on the electrical variables at stake.

Keywords: Railway model, Energy savings, Electrical substations, ESS, Train

Sommario

Il lavoro svolto mira alla realizzazione di un modello in ambiente Matlab e Simulink che possa simulare un sistema ferroviario, in particolare per quanto riguarda le sue variabili elettriche, di modo da avere uno strumento adeguato a studiare e analizzare il comportamento di un veicolo ferroviario in condizioni di funzionamento nominale, ma soprattutto per saggiare l'impatto sulla linea ferroviaria che potrebbe prevedere l'adozione di componenti innovative atte a ridurre i consumi energetici e le conseguenti emissioni inquinanti nell'attuale scenario di riduzione di impatto ambientale. Uno dei punti chiave è quello di avere un modello che sia il più possibile flessibile e adattabile a situazioni differenti da quelle di iniziale progettazione, di modo che l'implementazione di nuovi componenti sia la più rapida possibile.

Pertanto, si inizierà mostrando l'attuale stato dell'arte della tecnologia ferroviaria, con particolare riferimento alle linee alimentate in corrente continua a 3000V, essendo questa la tecnologia prevalente in Italia. Verranno perciò analizzate le sue principali componenti, dalle sottostazioni elettriche che l'alimentano, ai treni che ne rappresentano gli utilizzatori maggiori, senza trascurare la catenaria attraverso cui tutti i gli elementi sono collegati. Verrà inoltre dedicato un breve spazio anche alla tecnologia relativa alle linee ad alta velocità e capacità, alimentata da un sistema in corrente alternata monofase.

In seguito, verrà descritta la modellazione dei varî componenti che andranno a costituire il modello stesso ponendo attenzione alle ipotesi realizzative e motivandole; quindi verranno esposte alcune strategie atte a ridurre il consumo energetico dell'intera infrastruttura agendo sul recupero dell'energia rigenerata dai treni in frenata e attualmente poco riutilizzata.

Infine, dopoché il modello sarà stato validato e i suoi risultati verificati, verranno mostrate alcune simulazioni che riguardano l'applicazione di due strategie di riduzione dei consumi e i conseguenti effetti che hanno sulle variabili elettriche in gioco.

Parole chiave: Modello ferroviario, Risparmio energetico, Sottostazione elettrica, SSE, Treno

1 Introduction

Energy efficiency is becoming more and more important in these years, not only for economic factors, but also for environmental and political reasons.

As can be seen from *figure 1.1*, an important percentage of polluting emission, 14% [1], can be addressed to transportation systems, and this fraction is twice as much in a developed country such us USA (*figure 1.2*) [2]; so, they are a natural candidate for reducing waste of energy and greenhouse gas (GHG) emissions, having, at the same time, a significative reduction of the operating costs.

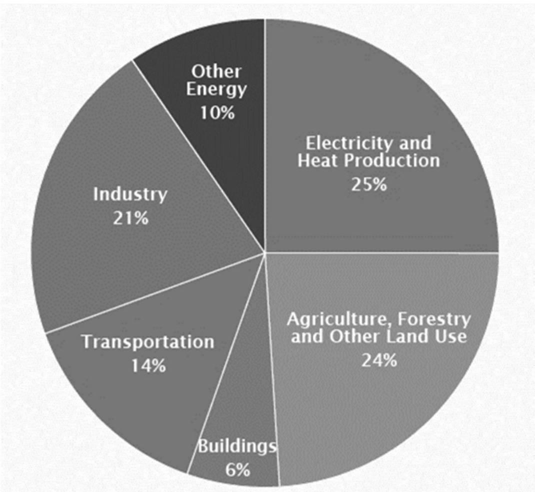

Figure 1.1 Global Greenhouse gas emission by economic sector (2015)

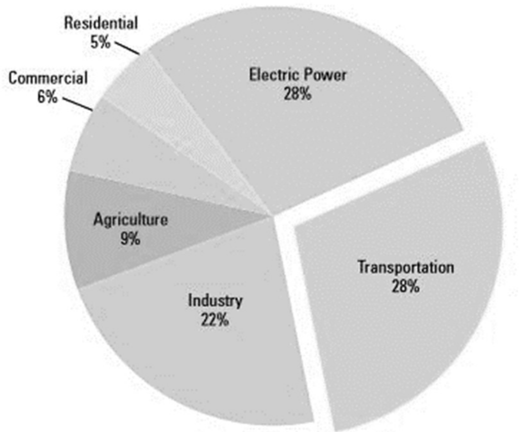

Figure 1.2 USA Greenhouse gas emission by economic sector (2016)

In this field, a promising sector is electrical traction, in particular electric railways, even though the share of emission can appear quite negligible, 2%; this is not completely true, because the traffic in this sector is increasing and it will be so in future [3], in order to reduce the transport percentage of light and heavy duty vehicles both for people and goods, because tracks have higher emissions for passengers or tonne for kilometres than trains ([4] see *table 1.1* for details) and it is more difficult to act on them to reduce emissions. Moreover, in the last 25 years, looking at USA situations, the total GHG emissions due to rail transport have an increase of 3.9%, so it is possible to act to reduce them with some enhancements, to align their variation to the one of aircraft or at least of ships and boats that are, respectively -10.7% and

-5.7%. Another factor that pushes the improvement of efficiency is the European target for 2020, for which railways have to reduce their emission by 30% [5].

Vehicle	**gCO_2 per passenger km**	**Vehicle**	**gCO_2 per tonne km**
Car (small petrol)	115.9	Petrol van	448.8
Car (big diesel)	227.8	Diesel or CNG van	271.8
Taxi	161.3	Rail freight	21.0
Motorcycle (125cc)	55.0-86.0	RoPax ferries	384.3
Motorcycle (1130cc)	145.0	Small tanker	20.0
Bus	107.3	Large tanker (100kt)	4.0
Train (international)	17.7		
Train (national)	60.2		
Ferry	115.2		

Table 1.1 Emission of passenger and freight vehicle per km (data from [4])

For electric trains, it is possible to improve the overall efficiency through regenerative braking, using the same motor which is used in the acceleration; this system is already employed, because it also allows to reduce the usage of pneumatic brakes with some benefits both in safety (in railways with long gradients the prolonged usage can cause some problems) and in reduction of temperature rise in tunnels [6]. However, nowadays, the common situation is a partial usage of the regenerate energy; indeed, it is only used for on board auxiliary services or by other trains along the line, if present, which are accelerating. Otherwise it is dissipated by dedicated on board rheostats, because this energy cannot easily pass from the DC railway line to the AC grid. The DC traction systems electric substation generally are not reversible, because the used technology is based on Graetz bridges, which do not allow a bidirectional power flow. Of course, this problem is absent in case of AC railways systems, where the regenerated energy can flow to the grid, through the transformers. However, a complete change from a DC to an AC line is hardly affordable, so this solution cannot be considered, apart from new lines.

1.1 Thesis purposes

The aim of this thesis is to develop a software simulator which allows to have affordable energy and electrical data that can be used in absence of measured ones (to reduce costs or because it is not possible to have real data) in deciding the best recovery strategy. It was already available a block oriented model which simulates the behaviour of a train on a given path, however it has some problems related to reusability. For this reason, it has been decided to create an object oriented model, which can be more easily manipulated in case different configurations should be tested, because it is generally more flexible than a block oriented one; besides, with such a model, the electric variables are all available without an internal hierarchy and a prescribed flow, which avoid further manipulations to find them and reduce the possibility of compilation errors. Of course, even this model is valid under some assumptions, but they are less stringent than the ones for block-oriented model. A disadvantage of this solution is the simulation time, which is generally higher than the one needed by the block oriented, because the numerical solver has to solve Differential Algebraic Equations (DAE) instead of Ordinary Differential Equations (ODE), so it has to differentiate DAE several times (as much times as the DAE index) to transform them into ODE and then solve the equations; for a block oriented model, this work is done by the programmer, who prescribes a flow for signals.

The thesis will firstly explore the technologies used in Italian rail traction system, analysing the actual state of art of the infrastructures necessary for DC railways, with also a brief overview of AC lines. Then the Simulink Simscape model will be presented and explained in its main parts and there will be displayed the actual available solutions that can be employed to recover the energy created by regenerating braking, focusing on DC railways, because the majority of the Italian network uses this technology. Successively, there will be a section about the interpretation of measured data coming from the trains, obtained by different measurement systems, and a comparison between them and the simulated ones, in order to check the correctness of the model for validation. Finally, the model will be used to test some case study that can bring improvements for railway consumptions and line voltage.

2 Italian rail traction system

In Italy there are two separate technologies for electrical rail traction feeding, in fact for the High Speed lines it is used the European standard that is a monophase 25kV AC at 50Hz, while for the other trains that cover national, regional and suburban paths it is a 3kV DC. In this thesis the focus is on this last, which represent the majority of Italian lines. For what concerns the rolling stock, it is quite various, because the trains have been acquired in different times, someone has been reconditioned, moreover even the high-speed trains use this line when it is not present their dedicated one.

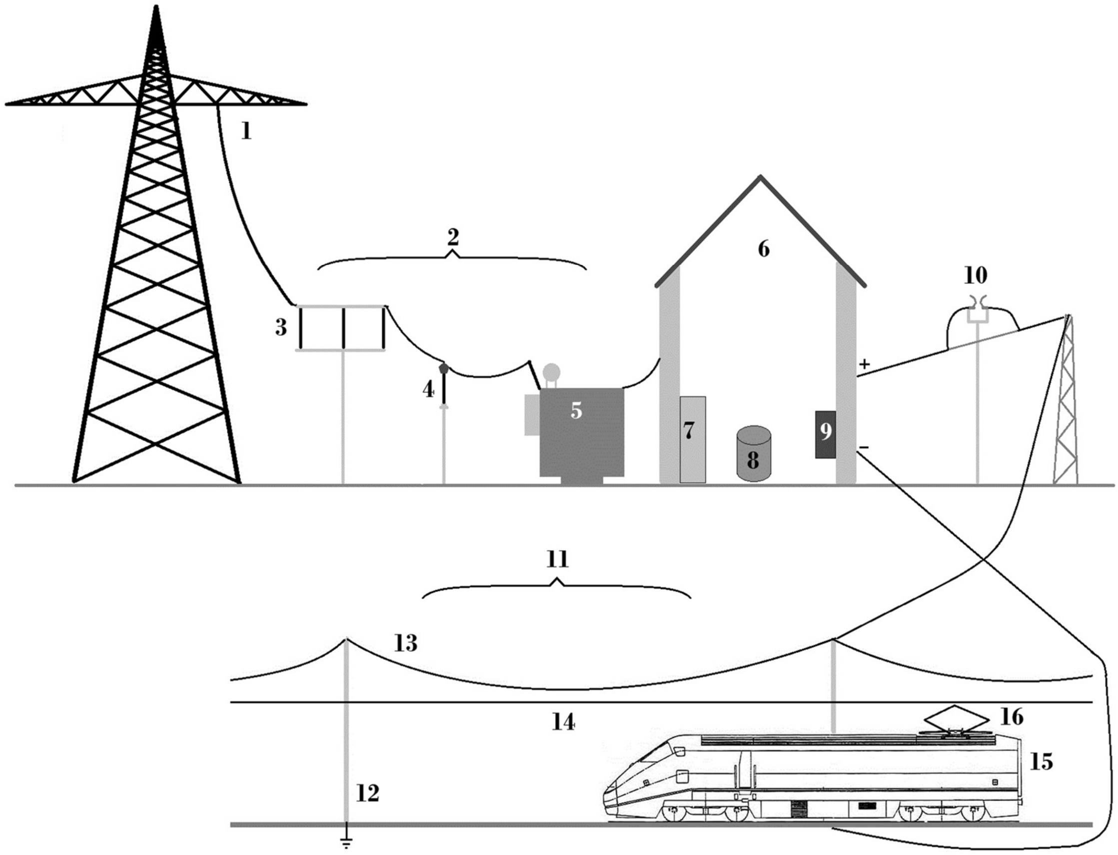

Figure 2.1 Main components of a rail network:
ESS: 1 High voltage grid and primary lines; 2 High voltage department; 3 High voltage disconnectors; 4 High voltage switches; 5 Transformer; 6 3kV DC department; 7 Rectifier; 8 Output filter; 9 Extra-rapid switch; 10 Air disconnectors.
11 Catenary; 12 Mast; 13 Messenger wires; 14 Contact wires.
15 Train; 16 Pantograph.

In the following there will be explored the main components of the Italian rail traction system, which can be seen represented in *figure 2.1*; most of information are taken from [7], [8], [9], [10] and [11].

2.1 Catenary

With "catenary" it is intended the electrical line that feed the trains travelling in a given path with the energy coming from the electrical substations: it is mainly composed by some protection systems and by the contact lines and the rails, in which the current flows, in fact the rail are electrically connected to trains and also to the electrical substations through the wheels.

2.1.1 Contact line

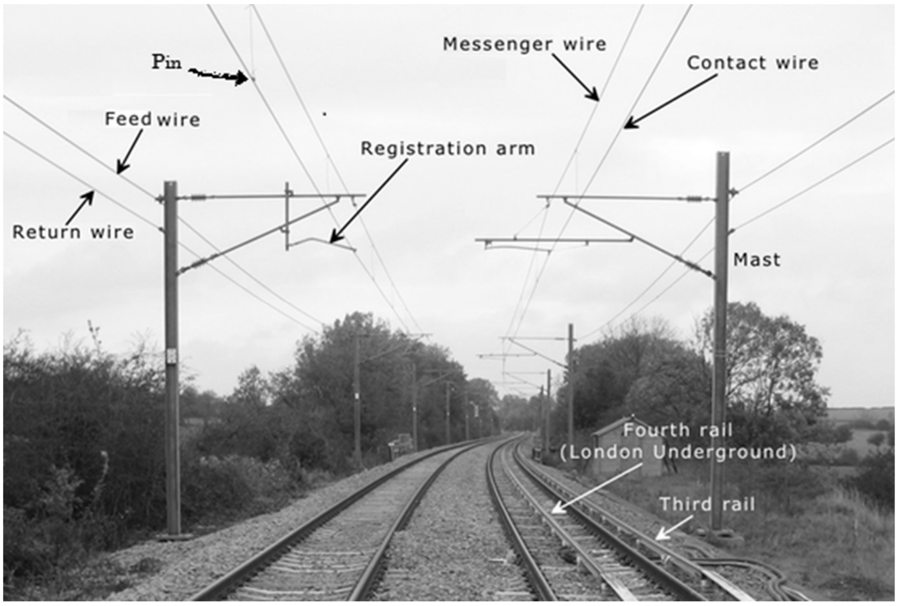

Figure 2.3 Catenary parts

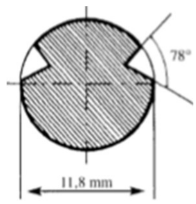

Figure 2.3 Contact wire section

For more important rail lines, the contact line is composed by two (otherwise it can also be single) copper contact wires substained by two messenger lines which are connected throug pins placed at a given distance. The messenger line is supported by masts equally outdistance (about 60 meters in straight paths, less when there is a curve) and is electrically isolated by them; it assume a catenary disposition (from which the name) so the pins must have different lengths in order to maintain the contact wire in the horizontal plane at the correct heigth that is 5m (in case of particular needs, like in a gallery, the distance from the trak can arrive up to 4.65m).

The contact wire is placed in the horizontal plane, but is not straight, it has a zig-zag shape, symmetrical with respect to the axis, obtained by the registration arms that place the contact line alternatively 20cm on the left of the binary axis and 20 cm on the right: in this way the pantograph is equally consumed by friction.

A counterweight system with pulleys guarantees that the messenger lines are still in the correct tension and prevent variations in catenary shape due to temperature deformations.

For what concerns line data, the section of a contact wire can be seen in *figure 2.3*, the particular shape is necessary for the adesion of the pins, and a tipical value for the area is 100mm^2. Instead, the messenger line is composed by 19 weaved cables, each one in copper with a diameter of 2.8cm.

In *figure 2.2* it is also possible to see the third (and forth) rail: this is an alternative to the air line, used in the past even in Italy, when the electrification was at the beginning. The third rail powers the train in an analogous way of the contact wire. Altogh this solution is less expensive then the catenary, it is not used in Italy (apart from some undergrounds, such as the red line in Milan), because it is less safe, since more easily reachable for a passer-by or a vehicle.

2.1.2 Protection system

The protection system is a ground circuit which connect all the metal structures and equipment in order to avoid a contact between them and conductors. To this aim all the mast have a ground pin, moreover are connected by aluminium cables, to guarantee a ground resistance inferior to 5Ω. In addition, the circuit is divided into 3km sections separated by voltage valves that close when the voltage overcome a threshold value: this will cause a high current that will signal the fault and that will be stopped by current protection switches.

2.2 **Electrical substation (ESS)**

The electrical substations role is to power the rail network, through the contact wires, with a nominal 3kV DC voltage: so, it is necessary to decrease the triphase primary voltage that enter in the ESS, which is connected to the high voltage or medium voltage grid, and to rectify it.

Nowadays, the ESS do not maintain exactly the nominal voltage, but 3.6kV, which is the higher continuative admissible voltage, because of the increased rail traffic, furthermore the medium train power is significantly increase since the 3kV DC standard has been adopted in Italy; in fact, a higher voltage, with the same power, brings a reduction in current amplitude and consequently in Joule losses.

The disposition of electric substations is calculated in order to guarantee that in every section of the line the voltage remains above the inferior limit of 2100V (which is the 70% of the nominal value), despite of the drops due to catenary resistance. To this aim, the medium distance on most important lines is about 20km but it can vary depending on the circumstances. The common situation is a bilateral power of the contact wire: the ESS are present at both extremities of the segment and connected with the positive pole to the contact line and with the negative to the rail, through a bar called "omnibus"; however, it is also possible that a segment is powered only by one ESS.

In Italy, the ESS nominal power can be 3.6MW or 5.4MW, which is usually sufficient to manage the case in which one of the adjacent substation is out of service.

2.2.1 Primary lines

The primary lines connect the ESS to the high or medium voltage grid, in the first case the common values are 200, 132 and 66kV, in series or in junction, in one case there is a switch that can interrupt the continuity of the primary line, while for the second, the connection bar switch, when open, interrupts the power to the substation but not the line continuity.

In some cases, a unique source fed more ESS in a loop, with some protections based on relays that acts when there is an overload or a short circuit between the phases, both when this is an isolated phenomenon both when it is a permanent one: anyway, these protections exclude only the part in which there is the fault letting operative the others. Moreover, in order to further reduce the possibility of a fault, is common to connect the electrical substations to two primary lines, to guarantee a double power source, to have redundancy: then, inside the ESS, there will be decided what to use, in ordinary operating conditions.

2.2.2 ESS generalities

The equipment of an electric substation can be divided into two groups, called "Reparto Alta Tensione" ("High Voltage Department"), placed on the open air, and "Reparto a 3kV c.c." ("3kV DC Department"), placed in a building, which can be easily distinguished in *figure 2.4*.

Figure 2.4 Electrical substation

2.2.3 Switches and disconnectors

Outside there are the transformers, the switches and the disconnects. The first, from the HV line are the HV disconnects, whose function is to separate part of an electric circuit, and must be used only in absence of load, so when the switches downline of it are open. This element is composed by three columns, one for each phase, connected in their top part by a rigid bar that can rotate around the axis of the central column, when it is required to open it. The rotation can be manual or actuated by an electrical motor and with some protection blocks that prevent the action when the switches are closed.

The HV switches are three polar and protect the primary lines from short circuit and overloads, so can be used even in presence of a load: they guarantee the current interruption and the insulation and are made of porcelain, while for the operation there is a pneumatic actuator.

2.2.4 Power transformers

The power transformer has three winds, one for the primary in star connection and two secondary in delta/star connection with a transformer coefficient that can vary during the operation in case of necessity and with an apparent power of 5.4MVA.

Figure 2.5 Power transformer

The refrigeration is guaranteed by the oil in which the transformed are immersed and whose temperature is maintained under control by a series of alarms that signal heating and, when the temperature is too high (over 70°C) act directly on the switch to isolate the electric component. Moreover, there is also a drain that collect possible oil leakages to decrease risks due to its flammability and toxicity. There are also some internal protections that signal and switch off the transformer when there are internal faults due to a gas creation.

A different kind of transformer is also used for the measuring instruments, which do not act directly on high voltage circuits, but measure the values at the transformer secondary that reduces the current or the voltage depending on the interesting variable.

2.2.5 Rectifier

Once the voltage has been reduced, the next step, happening inside the building, is to obtain a DC voltage from the 50Hz AC three-phase. The majority of Italian ESS use a passive three-phase Graetz bridge rectifiers, which guarantees a unidirectional power flows from the AC to the DC side and bases its success on reliability and robustness, but also on the minor cost with respect to solutions based on the power electronic. The technology upon which it is based is diodes, and this is the cause of its easiness, in fact the conversion can happen without the necessity of a controller: in *figure 2.6* it is possible to see the electric scheme of this rectifier.

The bridge is ideally composed by six diodes placed in two legs divided in two commutating groups, upper and lower, which are independent one another. In reality, the valves are more than six, this is a simplification, but it is acceptable because it represents what is seen from the external point of view. The reason of a greater number is that a disposition in parallel and in series allows to reduce the current and the voltage on each single component, moreover it can also guarantee an improved reliability if the equivalent diode is accurately oversized, because a fault in a single diode does not cause the fault in the entire half leg.

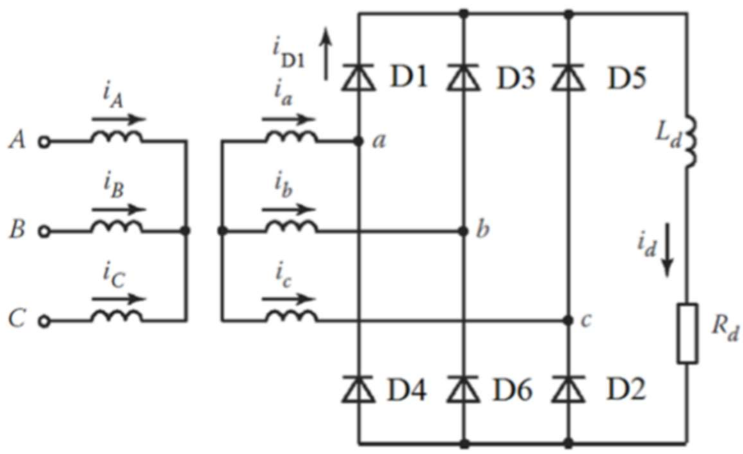

Figure 2.6 Electric scheme of a six-pulse Graetz bridge rectifier

The two commutating groups are composed each one by three valves, one by the ones characterized by an odd number, the other by an even number and in any configurations, there is only a half leg that is active, in particular for the upper group, where they share the same cathode, the conducting diode is the one with the highest positive anodic voltage, while, on the contrary, in the lower group, with the anode in common, it is the one with the lowest cathodic voltage.

Since the phase between two phases is 120° and that there are three branches, the commutation index $q_i = 3$, where q_i is defined as the number of commutations of currents belonging to the commuting group in a single period of the sinusoidal input voltage. Besides, since the two commuting groups are in series the pulsation index, that is the number of pulses in a period is $q_v = 2 * q_i = 6$, as can be noted in *figure 2.7*. Taking in consideration the first time interval with a complete pulse, so $30° \leq \omega t \leq 90°$, v_a is the greater voltage, while v_b is the lowest, as a consequence the active valves will be D1 and D6, so that $v_d = v_a - v_b$

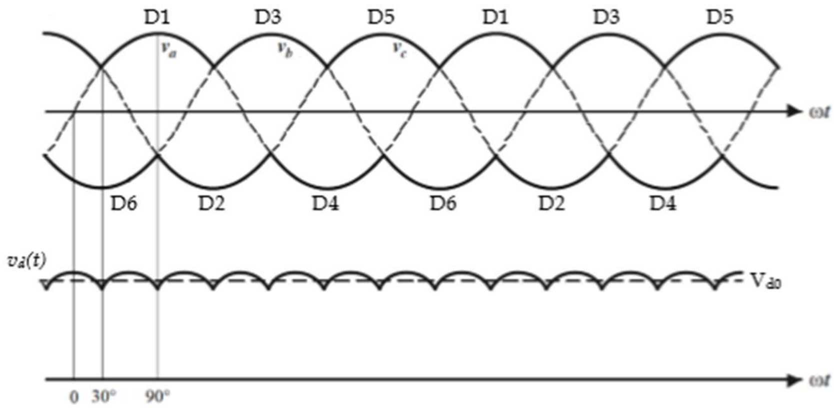

Figure 2.7 Phase and rectified voltages

An alternative to the six-pulse Graetz bridge rectifier is an analogous twelve-pulse, realized connecting in series two three-phase Graetz bridges powered by two secondaries of a transformer with three windings: the first bridge is fed by the star connected secondary, while the second by the delta connected (the transformer configuration is the one used in the ESS and already explained), the type of connection, in fact, does not cause any problem in rectification.

This alternative configuration ensures that the voltages of the second winding are 30° out-of-phase, in this way the indexes increase and there will be $q_v = 12$, so the resulting output will have more pulses, the double, and, at the same time, their amplitude will be smaller, with the result of a flatter DC voltage in output. This is the solution commonly used in Italian ESS: the power that these rectifiers can guarantee is usually 3.6MW or 5.4MW, depending on the choice in building phase, however these components can also support overloads of 100% for two hours and of 200% for five minutes. In addition, there is also a temperature control which activate fans when a threshold is overcome and arrives to open the switch in case of the temperature became too high.

Tanks to the more and more sophisticated power electronic techniques, nowadays, there is also the possibility to have reversible ESS, in this case the rectifier is not made of diodes but by thyristors and can also work as an inverter. This solution brings some benefits (that will be widely discussed in *section 4.3*), but it is also more expensive and less reliable than a classic Electric substation, furthermore they are not very common in Italian scenario.

2.2.6 Output filter

The shape of the rectified voltage is not completely flat, even in case of a twelve-pulse rectifier, and it is possible to demonstrate the presence of some harmonics that can disturb the rail utilizers and also other lines in the neighbourhood, such as the telephone communications, whose lines can have problems transmitted by induction from rail. To prevent these phenomena a filter is placed in output of the ESS: it consists of a great inductance in series to the positive bar and a battery of capacitors between the positive and negative bars.

Figure 2.8 Output filter

After the filter, there is a measuring cell that takes under control the DC electrical variables, and so the output voltage level, the absorbed current and the delivered power, and contains both the instrument to read these values, necessary for the operators, and the ones that register the trend which will be used for off-line analysis.

2.2.7 *Extra-rapid switch*

The role of these component is to protect the contact wire from the overcurrent that can arise form a short circuit on the line or on a vehicle; they work with a DC current and can support a maximum voltage of 6000V: they are able to automatically interrupt it in very short times (20-50ms), when the threshold is overcome. The actuator is magnetic, in fact there are two windings, one for the opening in which the overcurrent flows and whose flux is opposite to the one of the other wind, powered by ESS auxiliary services, so that when the limit is reached, the switch is activated.

Since it could be quite frequent the switch and it is not always related to a real fault, in fact an overcurrent can also be due to the contemporary acceleration of more trains in the same segment or to rapid short circuit inside vehicles due to pantograph movements, for example, the extra-rapid switches are able to automatically close when they detect that the line is isolated and the fault is solved. This is done through an auxiliary equipment that power the line through a given resistor and, at the same time, read the values of the electrical variables to detect the presence of short circuits. If the contact line results isolated, there will be no voltage drops and this will excite a relay that close the switch. However, as a further protection, after three auto-closures if the switch opens again it rests in that configuration until a human intervention.

2.2.8 *Surge protection devices*

After the extra-rapid switches there are also some other protections, a discharger at 3kV DC placed outside near the ESS building is connected to the output of each extra-rapid to protect it and the other equipment from over-voltages from the contact wire. It consists of a spark gap, a capacitor, a resistor and a ground pin.

Another device placed outside, at ESS exit, is the air disconnector at 3kV, easily recognisable for its shape, which allows to separate the circuit, through an actuator equipped with a small DC motor which rotates and divides the contact of the substation by the one of the circuit. The characteristic horns permit to interrupt currents up to 6kA without problems extinguishing the current arc.

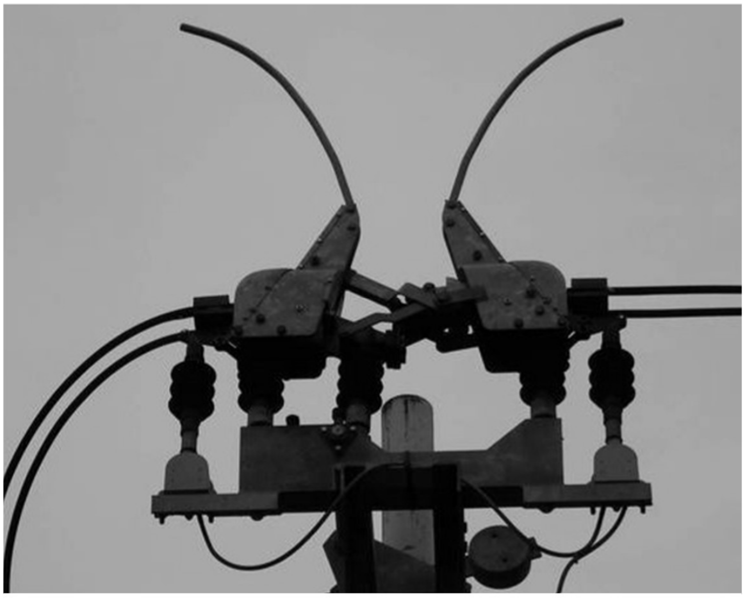

Figure 2.9 Air disconnector at 3kV DC

2.2.9 Mobile substation (MSS)

A mobile substation are train coaches equipped with all the devices of a normal ESS that are used when a substation is out of service or to increase the deliverable power for limited times.

When their service is required, the MSS is parked in the dedicated rail present in each electric substation and is connected to primary lines and to the catenary.

2.3 **Train**

The train is the utilizer of the rail infrastructure, so it is right to give some hints, not only from electrical point of view, but also about the mechanics and the measurement systems.

2.3.1 Mechanical system

The first step in analysing a train is the mechanic of the locomotive and its structure.

The motion of the train is assured by its wheels, which transmit a horizontal force to the ground that, tanks to Newton's third law, became an acceleration; however, looking at *figure 2.10*, it is possible to note that not all the wheel are equal in a locomotive, in fact on the extremities they have a reduced radius, while in the middle it is bigger, more than the double. The explanation is that these last are the driving wheels, while the others are simply supporting wheels. Nevertheless, nowadays this differentiation is less evident and, in some cases, absent.

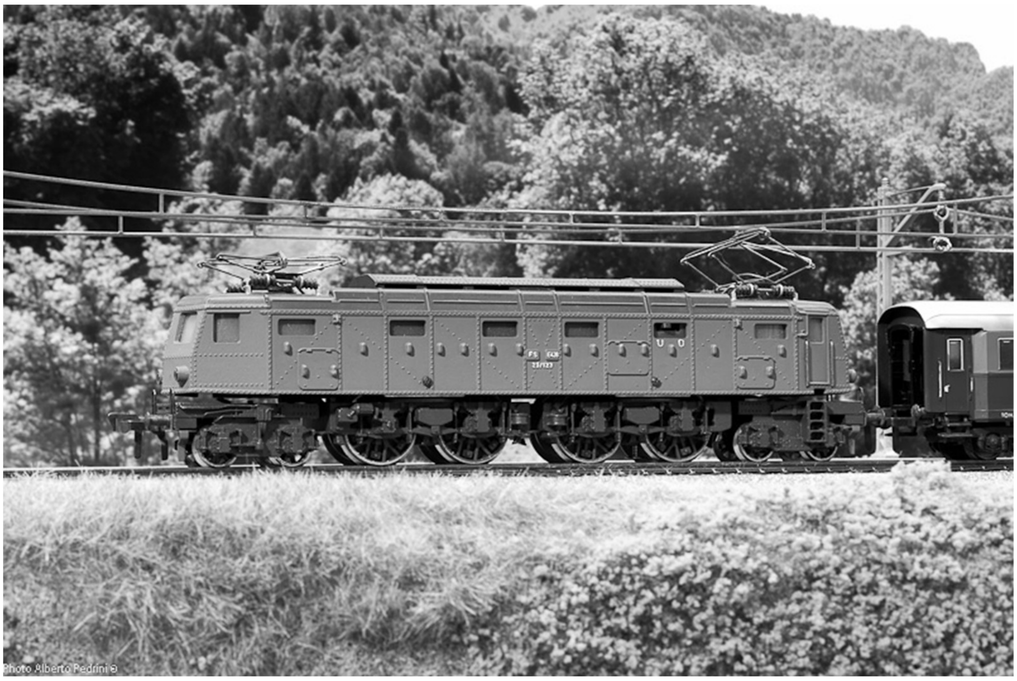

Figure 2.10 Train locomotive

All the wheels transmit parts of the weight to the ground, but only the driving ones also transmit a horizontal force that is the traction force. The sum of the vertical forces that rest on the bigger wheels is called adherent weight and will determine a limit for the traction force.

Before exploring force dynamics, it is necessary a small overview of the composition of a train: the wheels are not independent one another but are all parts of a wheelset that is composed by two wheels and an axle rigidly connected (*figure 2.11*).

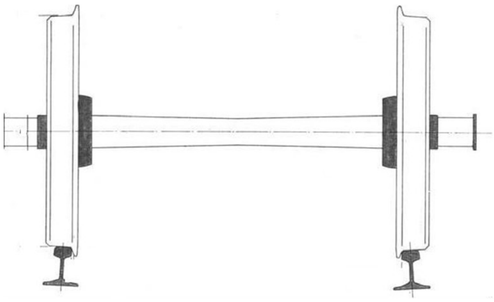

Figure 2.11 Train wheelset

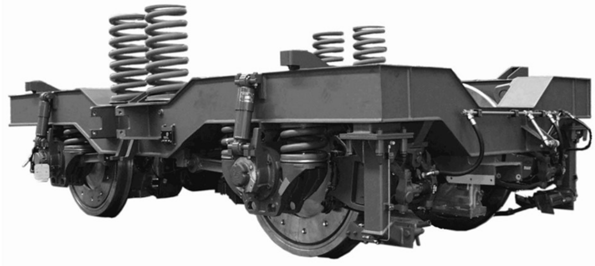

Figure 2.12 Train bogie

Then, two wheelsets are united to create a bogie in which can also be found the suspensions system of the train. A locomotive like the one in *figure 2.10* has 4 bogies, while a coach generally 2, because are only of the supporting type; each bogie is then connected to the frame in such a way that it can rotate of some degrees around the vertical axis in order to facilitate the train when it is in curve: since the coach is not flexible, it is fundamental that the part in contact with the rail, so the bogie, allows some degrees of freedom, otherwise it should be impossible to turn for the vehicle. A bogie with driving wheels can also contains the transmission equipment and even the motor, so its mass can be significantly increased.

Thanks to the integral composition of a wheelset it is possible to easily determine the train linear velocity in a straight rail as a function of the angular velocity ω and the wheel radius R: $v = \omega * R$. Of course, this is valid under the hypothesis of a constant value for the radius, but it is acceptable because of the great number of control which the wheels are subjected to for safety reasons.

The wheels are not cylindrical, but conical because this is necessary in a curve, in fact, thanks to this shape, the contact surface change and this determines a larger radius of the contact circumference for the external wheel, while for the internal there is a reduction: as a consequence, considering the same rotation velocity ω, the linear speed of the external wheel will be greater than the one of the internal so that it can cover, in the same time, the slightly greater distance determined by the rails parallelism that in curve brings a bigger radius of the external.

The wheelsets are also equipped with pneumatical brakes which act on wheels or on some parts integral with them, depending on their position, and which are generally used only at low velocity, because normally the deceleration is obtained by reversible electrical motors (of course, when present) that generate a braking torque and allows energy regeneration and a lower wear. Moreover, they are used in case of emergency, when is not possible to use electric brake. In some cases, it is also possible for the train to expel sand on wheels and rails in order to increase the friction force and to have a consequent reduction in braking distance.

For what concerns the mass, a passenger train is usually composed by two locomotives and a variable number of coaches, which depends on the line utilization and can vary from only one to a dozen, moreover it is not uncommon to see convoys constituted by two trains connected together: this a procedure used with the trains in which is not possible or not simple to divide the locomotive from the coaches, and this artifice is required in the hours when there are more passengers. The mass so can be estimated as

$$M_{train} = n_l * M_l + n_c * M_c + n_p * m_p$$

where n_l, n_c, n_p are the number of locomotives (from one to four, in general), coaches and passenger respectively, while M_l is the locomotive mass that is usually heavier than coaches ones, M_c (for an ETR-500, the train that will be analysed in the following, $M_l = 68t$ while $M_c = 48t$). Finally, m_p is the passenger mass, which can be taken as the medium mass of Italian people, 66,6kg, in fact knowing the exact passenger mass would be quite difficult and besides not very interesting, because it is only a small percentage of the overall weight, so in some cases can also be omitted, estimated as a percentage (3-4%) of each coach or calculated using the conventional load table in [12].

For a freight train the composition is more variable, generally they have more wagons, of different typologies, than a passenger one, especially if the path is long, and their total length can even arrive to a kilometre or more: for this reason, it is common to have a greater number of locomotives that is proportional to the total weight. Finally, in this case the load is not negligible, in fact it could also be greater than the wagon mass; however, for this case it is possible to evaluate it before starting with a good approximation, since the load mass should be declared.

It is not possible to declare a typical value for the mass, since it can vary from the 500 tonnes of a High-Speed train to the 200t of a Leonardo Express, the service that connect Fiumicino airport to Rome [], while regional and suburban trains are in the middle.

2.3.2 Force analysis

The forces that play a primary role in train motion are essentially three, and are linked by the equation

$$F = M_{train} * a + R_t$$

where F is the traction force, positive (in case of braking it becomes negative), and is an active force generated intentionally by the train to control its motion; $M_{train} * a$ is the inertia force and M_{train} is the mass of the entire vehicle which also consider the rotating mass; R_t is the sum of all the resistance forces. From this quick overview, it is clear that the presence of a positive traction force is necessary but not sufficient to increase the train velocity, because it should be greater than R_t. Au contraire, to have a deceleration is not necessary to have a braking force, because there are already the resistance forces in opposition to the motion, so the presence of a negative F only determines the value of the deceleration.

The traction force cannot be arbitrarily, in fact it is upper bounded by the adhesion force F_{ad}, which represent the maximum transmittable horizontal force between wheel and rail and is obtainable until the wheel is in pure rolling without sliding. The value of adhesion force is proportional to the weight through a coefficient f which is a function of train velocity, rail and wheel materials and humidity and neatness of the contact surfaces. So, it is possible to write

$$F_t \leq F_{ad} = f * P_t$$

FERROVIA	Trazione elettrica assi accoppiati	0,25 – 0,30
	Trazione elettrica assi liberi	0,20
	Trazione Diesel assi accoppiati	0,20
	Trazione Diesel assi liberi	0,167
	Trazione a vapore	0,167
STRADA	Asfalto	0,65 – 0,70
	Calcestruzzo lisciato	0,65 – 0,70
	Calcestruzzo ruvido	0,80 – 0,85

Table 2.1 Adhesion coefficient for tidy and dry surfaces

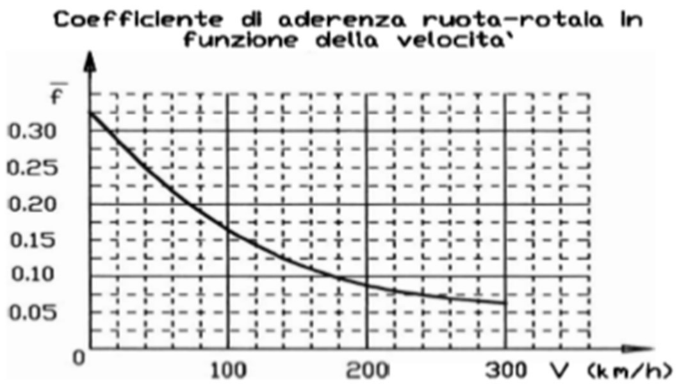

Figure 2.13 Adhesion coefficient as a function of velocity

In *table 2.1* it is possible to read tabled values for different contact surfaces and it immediate to note that for rail traction the values are much smaller than for automobiles, less than half: for this reason, there is the necessity of large curvature radii and small values of maximum declivity, moreover, the space needed for braking is significantly longer than the one for a car, at the same speed, also due to the bigger mass.

In *figure 2.13* instead, it is possible to see the decrease of f due to velocity, which is quite significative, for example at 200km/h it is a third than at start.

For what concerns the total resistance force, it can be seen as

$$R_t = R_0 + R_a$$

the sum of the resistance in straight line R_0 (essentially friction forces of different nature) and the accidental resistances R_a (curves and slope).

R_0 is composed by the friction between the wheel pivot and the bearing (R_1), the friction between rail and wheel (R_2) and finally by the aerodynamical one R_m, which is the main component at high speed, for a resulting

$$R_0 = R_1 + R_2 + R_m$$

There are some formulae to determine the specific resistance $r_0 = \frac{R_0}{P}$, which are adopted by Italian rail company, due to the difficulty to measure the correct value of each force, unfortunately these estimations (different for passenger and freight trains) are adequate at low speed, but not above 140km/h, because at these speeds the aerodynamic characteristic becomes important, so it is necessary to use the general empirical formula

$$R_0 = A + B * v + C * v^2$$

where v is the vehicle velocity, while A, B, C are coefficients identified through specific experiments and which are valid only for convoys of the same type of the one used in identification; to increase the validity of this estimation, it is better to identify the set of coefficient a, b, c that give the specific resistance r_0, because, in this way, they are independent from the mass, that is the variable more subject to changes, even during a route. Finally, a consideration is required for high speed trains, because the value of the resistance change in a tunnel with respect to open air, due to additional resistance.

The accidental resistance term can be decomposed in two as

$$R_a = R_d + R_c$$

where R_i is the resistance due to declivity, while R_c the resistance in curve.

The resistance due to declivity is simply

$$R_d = M_{train} * g * \sin\alpha$$

that is the component of the weight force that is parallel to the ground and so to traction force. This resistance is the only one which could be also positive, in fact when the train is travelling in descent, this force has the same verse of the velocity, so sustain the motion, however, from a control point of view, it is still a disturb.

The resistance in curve is originated from the fact that in this condition due to the wheelset parallelism inside a bogie there are some additional frictions because the motion is not pure rolling. In addition, these losses also consider the sliding of the external wheel in curve, which rest in spite of its conical shape, and the lateral forces against the rail that increase the overall friction. Since R_c is composed by such different terms, which cannot be measured, the only way to have a reasonable value is an estimation: it is proportional to train weight through a coefficient that depend from the radius called ρ, specific curvature resistance, and whose values, decreasing when the radius increases, are tabled (for details, see *paragraph 3.2.2*).

The sum of specific accidental resistance, r_a, and slope, i, give the compensated slope $i_c = r_a + i$, which is used to give to each section, long about 2km, in each direction of travel, of a rail line a performance grade ("Grado di prestazione" for Italian rail service): it is an increasing number from 1, indicating a flat or downhill segment, up to 31, a segment with a significative gradient and tortuosity, and it is used to indicate the motion resistance and consequently to define the maximum towable mass as can be seen in *table 2.2*.

Performance grade															
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Maximum towable mass (in dat)															
250	250	250	250	244	235	224	214	203	194	183	173	166	158	152	145

Performance grade														
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Maximum towable mass (in dat)														
137	130	123	118	114	11	104	101	95	90	87	83	80	74	69

Table 2.2 Performance grade and maximum towable mass

2.3.3 Train motor

Nowadays the train traction is mainly assured by electrical and diesel motors, while steam locomotive share is minor; since the focus of this thesis is on electrical rail, the diesel convoys will not be analysed.

The electrical motors that has been used in rail history are different, the first DC line train were equipped with DC motor, for their simplicity, however now they have been supplanted by triphase motors: the most common solution is to use induction machines, even though there are some high-speed trains that use AC brushless with permanent magnet motors, like AGV-575.

Before the motor, all the electric trains are equipped with an inverter, which allows not only to create a three-phase voltage from the DC catenary, but also permits to manipulate the electrical variable of interest.

It is possible to obtain an equivalent monophase circuit of the induction machine and use it for control, in particular it could be used the four parameters model in *figure 2.14*. This is possible considering a steady state condition, but it is not a restrictive hypothesis, because, although the motor has an intrinsic time constant due to its great inductance values and so it is not possible an immediate torque variation, the mechanical time constants are significantly higher particularly in case of a train, considering its mass; therefore the hypothesis can be accepted, without loss of generality.

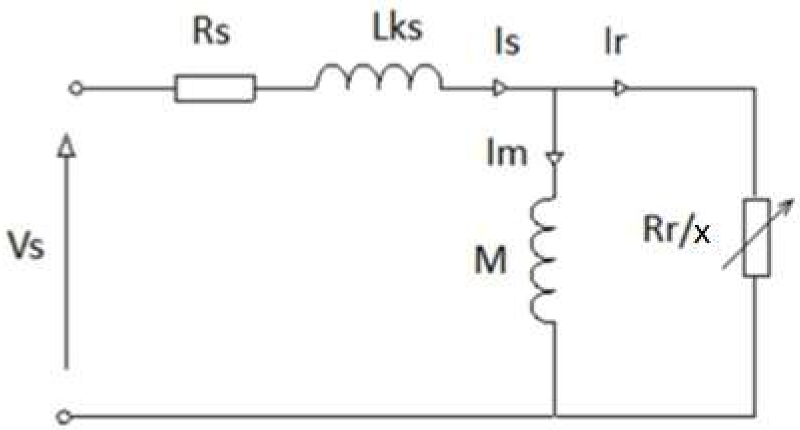

Figure 2.14 Four parameters equivalent circuit

At this point, it is possible to obtain the equations of the four parameters equivalent circuit with leakage on the stator side (identified by an "s" in subscript, while "r" stays for rotor):

$$\overline{V_s} = R_s\overline{I_s} + j\omega L_{ks}\overline{I_s} + j\omega M\overline{I_m}$$

$$\frac{R_r}{s}\overline{I_r} = j\omega M\overline{I_m}$$

$$\overline{I_s} = \overline{I_r} + \overline{I_m}$$

$$\overline{\psi_r} = M\overline{I_m}$$

$$x = \frac{\omega - n\Omega}{\omega}$$

$$T = nMI_mI_r = n\psi_rI_r$$

$$P_m = 3 * \frac{1-x}{x} * R_rI_r^2 = T\Omega$$

Where R_s and R_r are the stator and rotor resistances respectively, while L_{ks} is the total inductance bring at stator side and M is the mutual inductance with $\overline{I_m}$ the corresponding magnetizing current component; x is called slip, ω is the flux rotation speed (which corresponds to the electrical pulse), Ω the mechanical speed and n the number of pole pairs, finally T is the electric torque and P_m the power.

From equations, it is possible to deduce that the torque is influenced both by stator voltage and frequency: thanks to the power electronic it is possible to act on these two variables to obtain the desired torque. Until the machine rotates at low velocities, below base speed Ω_b, the velocity is proportional to the voltage, maintaining the same torque, so to increase velocity, it is necessary to rise voltage. When the voltage limit, determined by insulation level and by the power supply, is reached the motor velocity is $\Omega = \Omega_b$: if the limit in velocity must be overcome, it is necessary to act on rotary flux ψ_r reducing it as $1/\Omega$ in order to keep constant the mechanical power, of course, this will cause a torque reduction, in particular the rated one will decrease as $1/\Omega$, while the maximum one as $1/\Omega^2$, until Ω^* when the rated torque is equal to the maximum one, however it is possible that $\Omega^* > \Omega_{max}$, the maximum velocity reachable by the motor and determined by its mechanical limits.

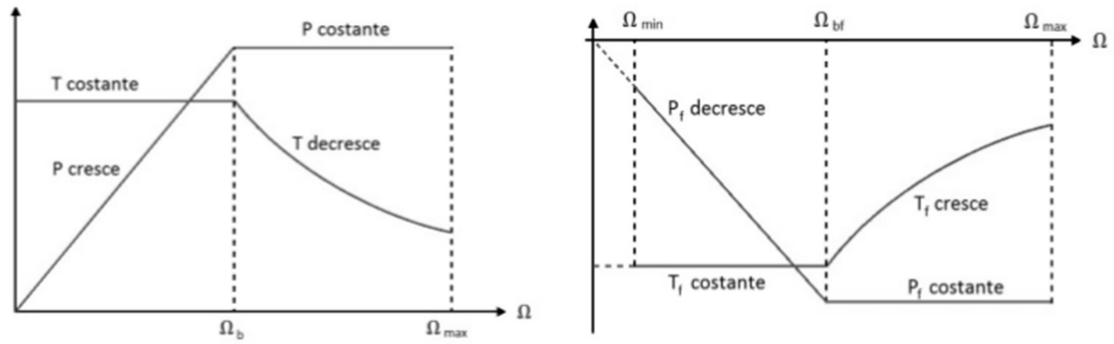

Figure 2.15 Induction machine operating field

In *figure 2.15* it is possible to see the operating field of an induction machine and can be noted the part at constant torque and the one at constant power. The procedure is similar during deceleration, when the machine acts as a generator, but the mechanical characteristics may be different; furthermore, now there is also a lower bound for velocity, Ω_{min}, below which the machine is not able to guarantee the braking action, so it is necessary the action of pneumatic brakes.

For what concerns the velocity control of the motor, there are different techniques, but the purpose is always to use the DC motor scheme with some modifications to adapt it to the induction machine.

2.3.4 Transmission

After the motor, a transmission box is required in order to have the right values of torque and rotation velocity, with its transmission ratio $\tau_t = \frac{\Omega_1}{\Omega_2} = \frac{T_2}{T_1} = \frac{1}{\mu_t}$, where subscript 1 indicates the velocity and torque entering, while 2 exiting and μ_t is the force transmission ratio. Obviously, this relationship is valid under the hypothesis that there are no frictions between transmission gears, so that there are no power losses in this component, the input power is equal to the output one.

In reality, there are always some losses that can be indicated with P_l, although they have a small value: in this case the equation that holds is $P_1 - P_2 - P_l = 0$, and it could be defined the transmission efficiency $\eta_t = \frac{P_2}{P_1}$.

2.3.5 Auxiliaries

In an electric train there are many auxiliary services which absorb a power inferior to the traction one but still significant in a power balance of the vehicle. In general, the energy is directly taken from the DC current or by the traction transformer through adequate converters depending from the fact that the type of each utilizer.

The most important auxiliary services are the oil pumps, the moto-compressor for pneumatic services, the fans used for the motor cooling, but also the air-conditioning and heating of coaches and other secondary services like lighting.

2.3.6 Measurement instruments

The trains have on board some measurement systems that provide data useful for the driver and to take under control the vehicle, however the focus of this paragraph is not on standard dotation, but on the particular measurement system installed experimentally on two passenger trains which supply data used for the simulations.

The measuring systems are two, called EMS and MVB, and are placed in two different position, because their function is different.

The MVB system measures the train data that come from the vehicle logic, for this reason they are usually coded, for example the line voltage is not expressed directly, but as an interval: there are 4 binary numbers, each one expressing a level (00: under 100V; 01: between 100 and 1900V; 10: between 1900 and 3400V; 11 over 3400V). Even the train velocity is not expressed in km/h or in m/s, but through an internal conversion; besides there are other information like GPS position and some internal data regarding, for example, the batteries voltage and current. Moreover, there are some indicators or flags that signal the status of internal components, commands or motion: they can be used to check if the pantograph is lifted, if the train is accelerating, braking or coasting, if the fans or the compressor are on automatic or switched off and so on. Then all these data are sent to a server in order to make them available for off line analysis, through the MCG junction box that functions as a GPRS gateway and is also used by EMS system for its transmission.

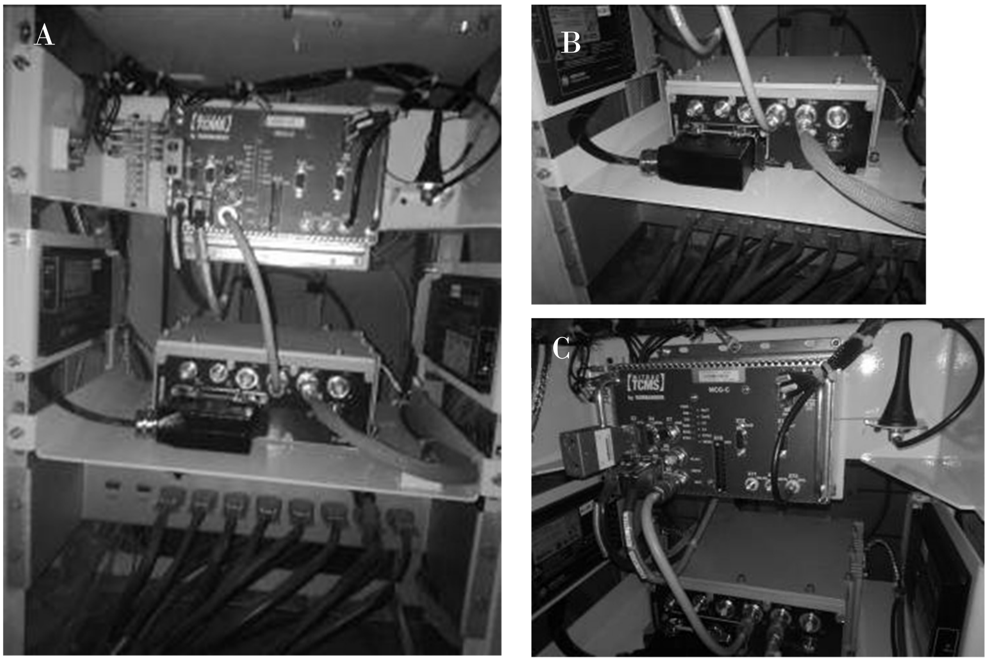

Figure 2.16 MCG and EMS junction boxes: MCG is shown separately in figure B, while EMS in C; in figure A it is possible to see how they are installed inside the train

The EMS system instead is used to measure the input current and voltage of the machine from the pantograph. For this reason, the sensor (in *figure 2.17*) has been installed before the IR (i.e. the protection system), in the left electronic island (in Italian “Isola elettronica di sinistra”, visible in *figure 2.18*): so, it can quantify the absorption of current and voltage.

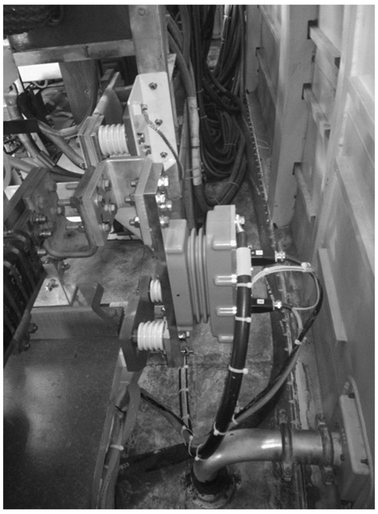

Figure 2.17 EMS sensor

Then they are sent to EMS junction box by an ethernet cable where they are elaborated to extract other quantity of interest like the consumed or generated energy, both active and reactive. Here also arrive GPS and distance data from MVB and they can be used to synchronize the two systems, with a greater precision with respect to the timestamp that can be shifted. Finally, the data are sent to another server from which they could be downloaded and consulted.

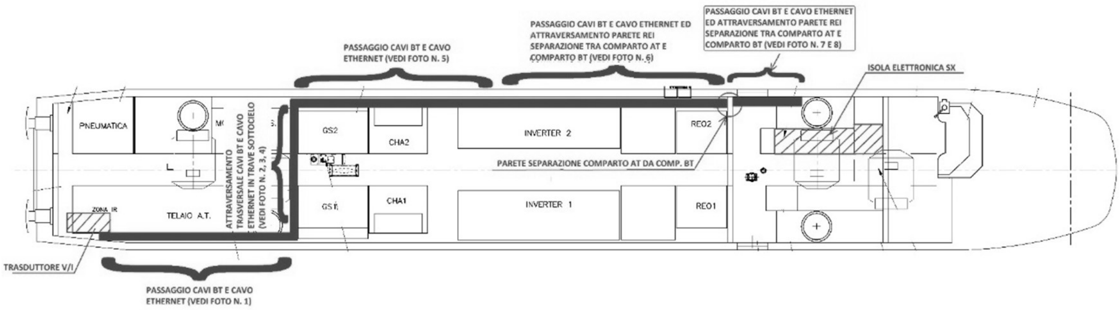

Figure 2.18 Locomotive internal structure

2.3.7 *ETR 500*

The additional measuring system is installed on *E.414* locomotives, that are the ones that equip the ETR 500 trains, used for the *Frecciabianca* convoys. This train has been studied to be used as a passenger train connecting the Italian most important cities, travelling at high speed; then they have been modified to adapt them to the *AC/AV* standards and the locomotives has been renamed *E.404*.

So, *E.414* locomotives equip high performance trains which use only the 3kV DC line. They are easily recognizable for their aerodynamical shape, necessary to reach high speed (up to 200km/h in their actual configuration) without too large friction losses.

Figure 2.19 ETR 500 Frecciabianca

The motor is assembled in the wheelset an is a three-phase induction machine equipped with a GTO converter which can act also as electric brake and regenerate energy, however it is also furnished with braking rheostats and with pneumatic brakes. The nominal power of the locomotive is 4.4MW assured by four motors, for a total mass of 68 tons, while the coaches mass is 40 tons.

2.4 AC lines

In Italy the *AC/AV* lines are minority and of recent construction, however they are along strategic vectors, in fact they link the most important cities and connect the north to the south, moreover new sections are being projecting and building to expand the network and create connection also with the continent and other principal cities as can be seen from RFI (which is Italian railroad company) project plan in *figure 2.20*. From December 2009, the line Torino – Milano – Napoli until Salerno is open, then also between Milan and Brescia and between Padua and Mestre new lines has been open for a total of more than 1000km. The purpose of these lines is not only passenger traffic, which has its importance and has moved to trains part of airplane utilizers, but also the improvement and strengthen of rail freight traffic.

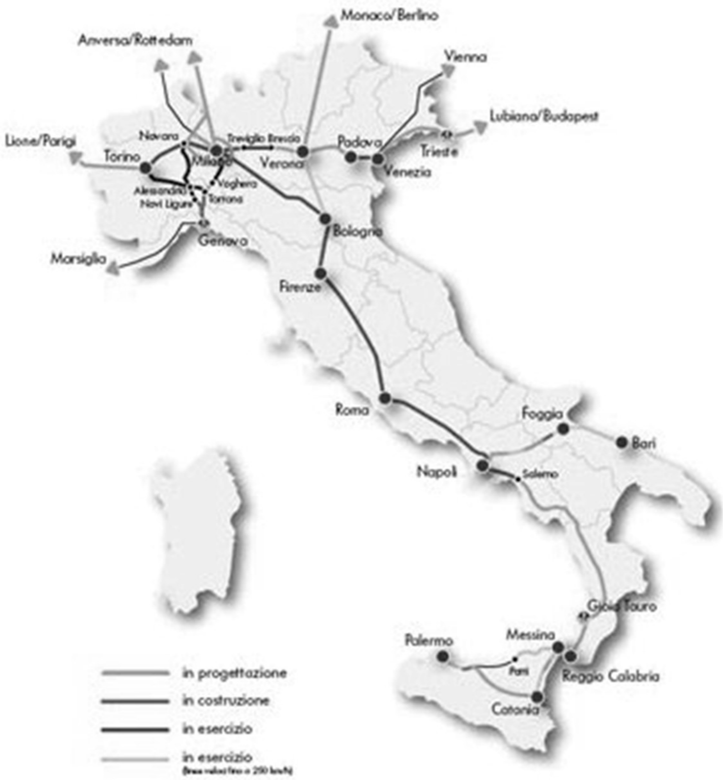

Figure 2.20 RFI AC/AV rail network project plan

The technology of these *AC/AV* lines is monophase 2x25kV at 50Hz and allows to reach velocities up to 300km/h, so with huge energy absorption, and with an elevated train traffics.

The advantages of this type of traction are multiple with respect to a classical 3kV DC: firstly, there is a higher potentiality, maintaining the same distance between substations, because of the high voltage (50kV) of the line that brigs as a consequence lower currents at parity power level and so more contained voltage drops. Another benefit is a reduced interference emission with respect to the environment, to third parts and existing rail plants, this because the rails subdivision in cells: in this way only in the cell where is the train the rails conduce current and so generate interference, while in the others there is no electromagnetic pollution; furthermore, even in the occupied cell the situation is better than the case of 25kV, due to the bilateral power, that decrease the current that flows in the wire and in the rail, reducing interferences. It may also happen, in the best case, that the disturbs cancels each other in a conductor placed in proximity of a cell occupied by a train and long as the cell itself, because, in its first half part it would be subject to an electro-motive force (e.m.f.) with a given direction, while in its second half to an equal and contrary e.m.f.

2.4.1 Line components

The characteristics of a 2x25kV line are different from the ones of a 3kV, in fact this system requires for a double rail line two feeder powered at 25kV and in phase opposition, in addition to the two contact wires at 25kV. Every 10-15km is installed a Double Parallel Place (DPP, "Posto di Parallelo Doppio"), which is composed by two autotransformers with a ratio 1:2 and an apparent power of 15MVA with their extremities connected to the contact lines and to the feeders respectively and the central pin to the rail; the rail section between two DPP is called cell. In each DPP, between the two autotransformers is installed a Neutral Section (NS); a NS is installed also in each substation. Near the boundary with 3kV lines, where the line change from AC to DC, are installed some Simple Parallel Place (SPP) which are equipped only with a single autotransformer. Finally, there are the electrical substations that power both the wires. Thanks to the higher voltage, the distance between them can be increased with respect to a DC line; in Italy, it has been chosen a potentiality line value of 2MW/km, so the medium distance between ESS is 48km, while for DPP is 12km, and are equipped with two transformers of apparent power 60MVA. Another difference is that for AC lines, the catenary is always powered only on one side, if there are two substations on its borders, each one will power only a half, furthermore, the cables are not in copper but in copper and magnesium to have improved mechanical qualities.

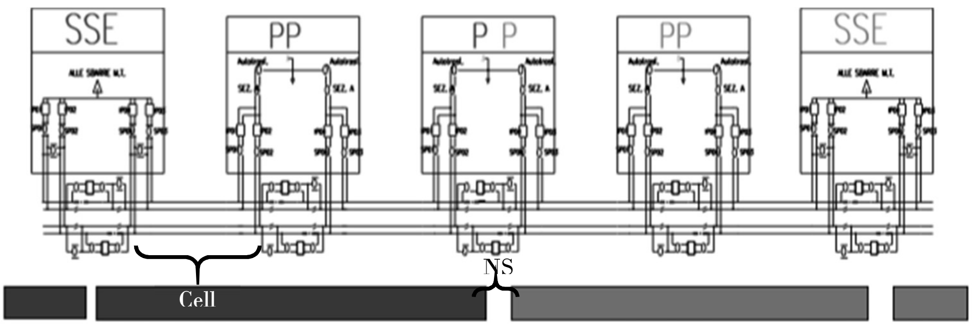

Figure 2.21 AC/AV line infrastructure disposition

From this quick overview, it is possible to note that there are more typologies of infrastructures involved with respect to a classical DC line, but their number, seeing the medium distance between them is not significantly higher.

2.4.2 Electric Substation

The ESS is quite easy, because it is essentially a transformer: there is a double power transformer which decrease voltage from HV to MV, then there are some line switches and power disconnectors that feed a wire and a feeder per transformer.

2.4.3 Double Parallel Place

Each DPP is equipped with two autotransformers but they are both working only in case of it the place performs the function of separation in addition to the parallel. In a segment between two substations there are three DPP and the central one is also a separator, so it will have the Neutral Section open to facilitate the change of power source. In case of necessity, the separation could be done by another DPP.

2.4.4 Neutral Section

A Neutral Section is placed between two ESS to divide the two subsections powered by the different substations to facilitate the change of phase; it is created by the central DPP, while the others double parallel places left their NS closed. Even in correspondence of ESS there are NS, even though here there is not any phase change, in order to increase the separation in case of substation fault. The length of the neutral section in the worst case is 150m; since in this part there is no voltage potential, if the train pantographs are at a distance lower than 150m, there could be the possibility of a phase-phase line short circuit, so a new NS scheme has been studied which reduce this possibility.

When there is the passage between AC and DC there is not a simple NS, but another separator that physically divides the two lines, not only in air but also at rail level with an adequate isolation junction, moreover there are some filters which prevent the current at 50Hz from going to DC line.

2.4.5 Catenary

The catenary of Italian *AC/AV* lines, as already mentioned, is slightly different with respect to the analogous DC one; in *figure 2.22* it is possible to observe a typical line section.

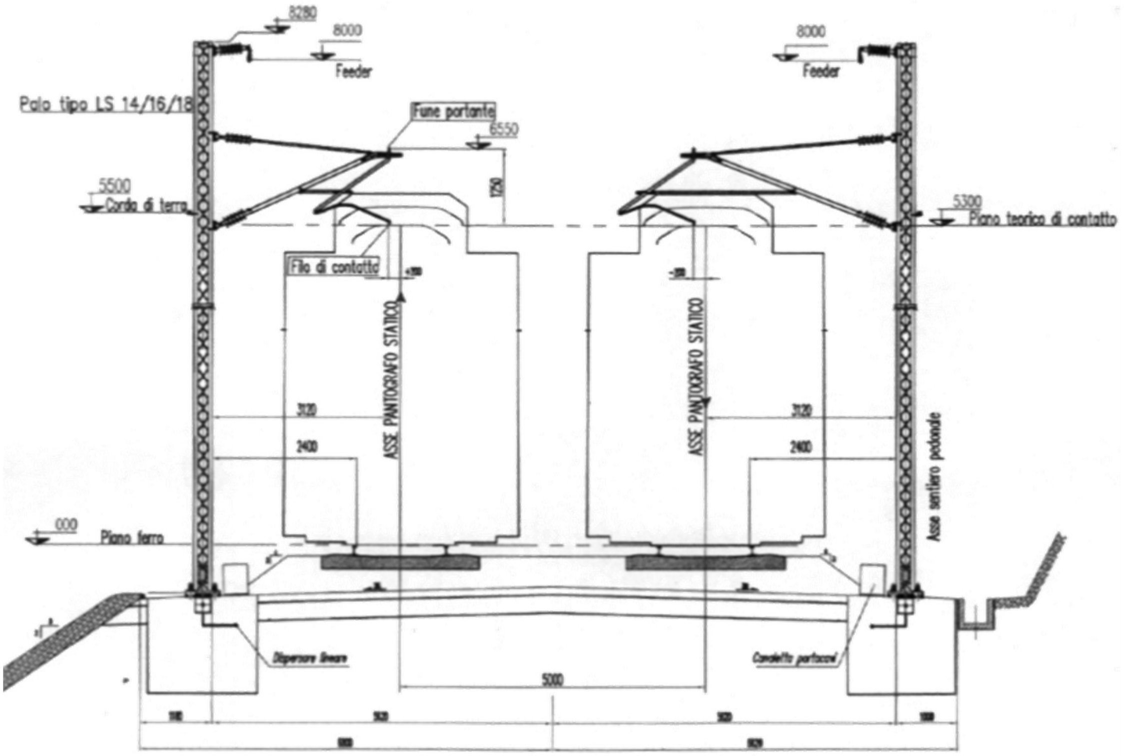

Figure 2.22 AC/AV line section

The messenger wire is made of copper and has a section of 120mm^2, while the contact wire can be in copper or in copper and magnesium in the last application because it guarantees a higher traction value and also an increased speed of propagation which assurances better performances at higher velocities. There are two contact wires, one kept at 25kV, the other at -25kV, both at 50Hz, of course, in order to have a monophase line with a potential of 50kV AC.

Finally, the feeder is composed by steel and aluminium, with a nominal diameter of 22.8mm and could be placed externally with respect to the rail or internally as in the case in *figure 2.22*: however, this last positioning is safer because it assures that in case of damages and consequent fall of the feeder, it avoid that the cable exits from the railway, therefore it is the standard in viaducts.

2.4.6 Protections

The HV line protection strategies are analogous to the ones used on the HV railway grid, all the switches, in case of current imbalance between the phases, must be ready to open in case of emergency, and also to auto close in three polar manner. If a further intervention happens they will stack open until human action.

The protection must be assured for each type of electrical configuration in that line segment and even when the power supply, generally guaranteed by two bipolar switches is powered only by one. Moreover, it must be efficient in case of short circuit between catenary and ground and feeder in each possible combination, even in case of particular arrangements like the case of a substation out of service, which cause, in the worst case, a repartition between the bordering ESS of 60 and 36km.

3 System modelling

The model has been created to simulate the behaviour of a train in a railway line, in order to have reliable data, which can be used in analysing a desired route, still existing or not yet, in absence of measured values.

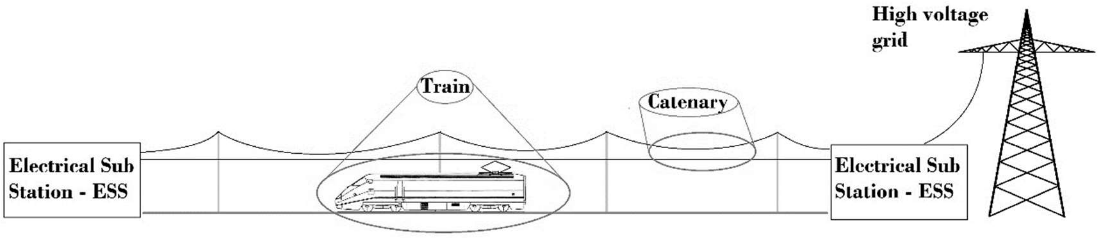

Figure 3.1 Main parts of an electrical railway line

For this purpose, the electrical railway line has been split into its main parts that have been modelled as the main Simscape components with which assembly the overall line model; in *figure 3.1* it is possible to see the three main parts highlighted: the train, which is the utilizer, the catenary, which is the DC bus that feed the train composed both of the electrical cable suspended over the train, but also of the rails and the Electric Sub Station, which converts the AC current taken from the medium or high voltage grid into the DC power inserted in the railway line.

The input signals used by the Object-Oriented elements are originated by the Block Oriented components, which evaluates the power, the distance covered and other internal variables.

3.1 System components

In order to introduce modularity in the model and improve the readability, some components representing the main elements of the rail have been declared as subsystems, so that they could be easily replicated inside the model itself.

Then, all the components have been grouped in a unique library, in order to have an easy access to them when a new model must be created.

3.1.1 Electrical substation (ESS)

There are several possible models for an Electric Substation, depending from its type; for the purposes of this thesis, it was chosen a basic structure of the classical ESS, with the possibility to add some possible extensions to cover cases in which there are additional components or to be closer to reality.

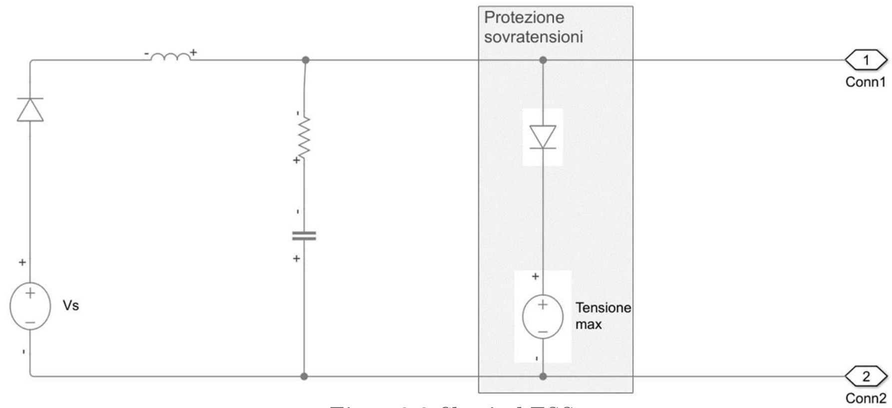

Figure 3.2 Classical ESS

In *figure 3.2* it is possible to see the equivalent scheme of a classical electric substation: it has been considered as a constant DC voltage source, which has, in series, a diode, because it can only deliver current, without the possibility of absorbing power; this part models the bridge rectifier, powered by the electric grid, considered at a constant voltage level. Then we can see the filter (taken, with the values of the correspondent electric elements, from [9]), composed by an inductance (5mH) and a resistor (10Ω) plus a capacitor (500μF). Finally, still in parallel, there is a protection from overvoltages similar to the train breaking rehostats.

The choice to model the ESS source as a constant voltage source is clearly a simplification with respect to the reality, but it is appropriate for the aim of this model; it was possible to replace it with the equivalent realization of a double Graetz bridge powered by the national HV grid modelled as a three phase voltage source, in fact it has been already done in other work thesis (not with Simscape, but with Simpower System, which is another object oriented Simulink library; however the realization procedure is not very different), but in that case the purpose was to study the electrical problems in its dynamics and transients, while in this one, it would be a complication which increases the simulation time without bringing a significative improvement; moreover also considering the national grid as a constant voltage source is a simplification, but in modelling one of the key point is to find the ideal trade-off between simplicity and validity of its results.

For what concerns the ESS as a voltage source and not as a current one, this has been done looking at some simple models presented in some papers ([13], [14], where the ESS was simply a constant voltage source with a resistor and a diode in series, without all the filters): it is a reasonable idea, because the substation must guarantee a constant voltage level, while the current delivered may change from zero, when there are no trains on that segment, to a maximum value depending from its power limitation.

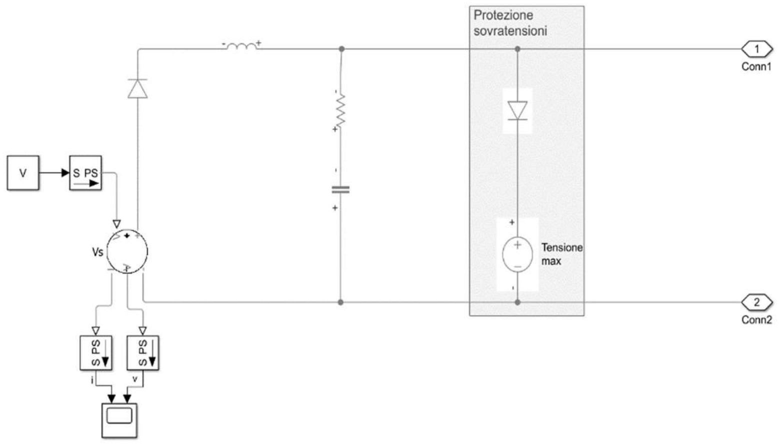

Figure 3.3 ESS with power limitation

This restriction is the base of the first implementation, the equivalent scheme of a ESS with power limitation (*figure 3.3*): it is very similar to the classical one, with the only difference that here the voltage source is a component ad hoc declared so that it deliver the desired voltage until the instantaneous power $P = V * i$ is minor than the maximum power that the substation can deliver; then the generator became a constant power source so $V = \frac{P_{max}}{i}$. It has been taken $P_{max} = 3.6MW$ accordingly to the Italian most common situation [7].

As can be seen, the desired voltage is given as an input as a constant value V in that figure, however it is also possible to give a varying value to mimic a controllable ESS: in this case, the input value is the one evaluated by the controller and can also assume negative values.

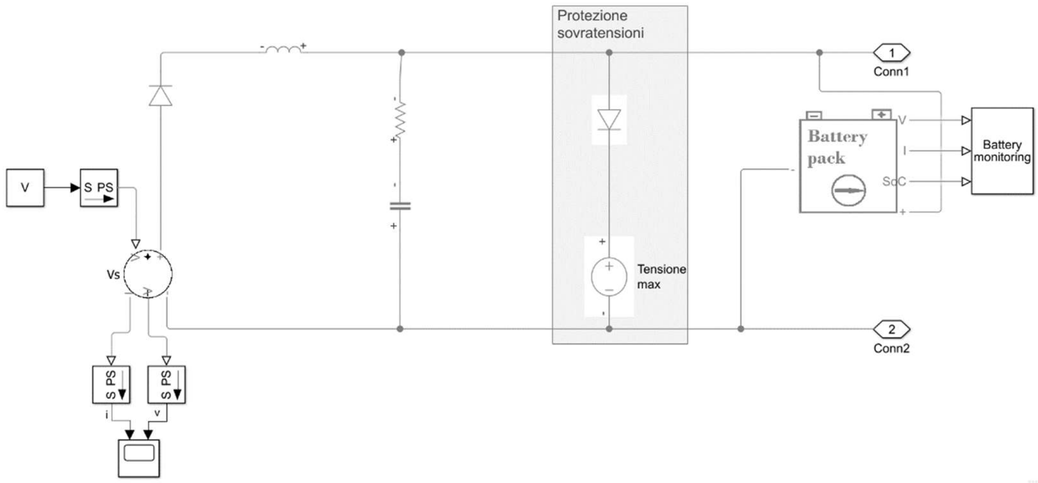

Figure 3.4 Reversible ESS with accumulator

The component in *figure 2.4,* models a classical substation with power limitations equipped with a pack of accumulators in order to make it reversible, so it can also absorb power: in particular, the battery absorbs energy from the railway network for charging when the ESS voltage overcame an activation threshold $V_1 > V$ (where V is the ESS desired voltage) and it is not greater than a maximum value V_{max}, over which the accumulator is detached from the network to avoid damages. A similar procedure is used for discharging, in fact, when $V < V_2$, the battery starts to deliver power to support the ESS.

In order to mimic this behaviour, a new battery pack component has been declared, in fact there were already some abstractions in literature, but they were too simply [15]; in *figure 3.5* it is possible to see how they are composed; for the battery part, there is simply a diode and a constant voltage source in series, similarly to breaking rheostats: in this way, if the electric substation reach a given threshold V_c, using the same nomenclature of the figure, smaller than the train braking rheostat activation value, but greater than V_s, the corresponding storage diode D_c starts conducing current, that can be interpreted as the current absorbed by the reversible substation and so regenerated. Therefore, this model can mimic only absorption moreover in a static and not completely realistic manner, and without considering the battery capacity, while the discharging is not modelled, consequently it was too limiting for the purpose of this thesis.

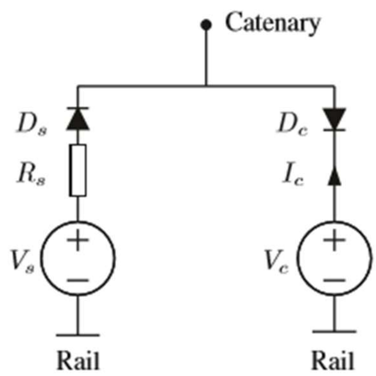

Figure 3.5 Model of a ESS equipped with battery pack used in [15]

The Simscape component "Battery pack" key idea is to model it as a current source with the V-I characteristic in *figure 3.6*: below $V_2 = 3400V$ there is a positive current, then, between V_2 and V_1 it is off, while if the voltage is between V_1 and V_{max} ($3700V$ and $3950V$, respectively in figure) the battery is in charge and so absorbs a current. The current entity depends on the accumulator characteristics and can be different in the two zones, moreover it does not change as a step, but it increases (or decreases) as a ramp for a voltage interval ΔV, here set to 200V, which can be modified in component mask like the other thresholds and parameters.

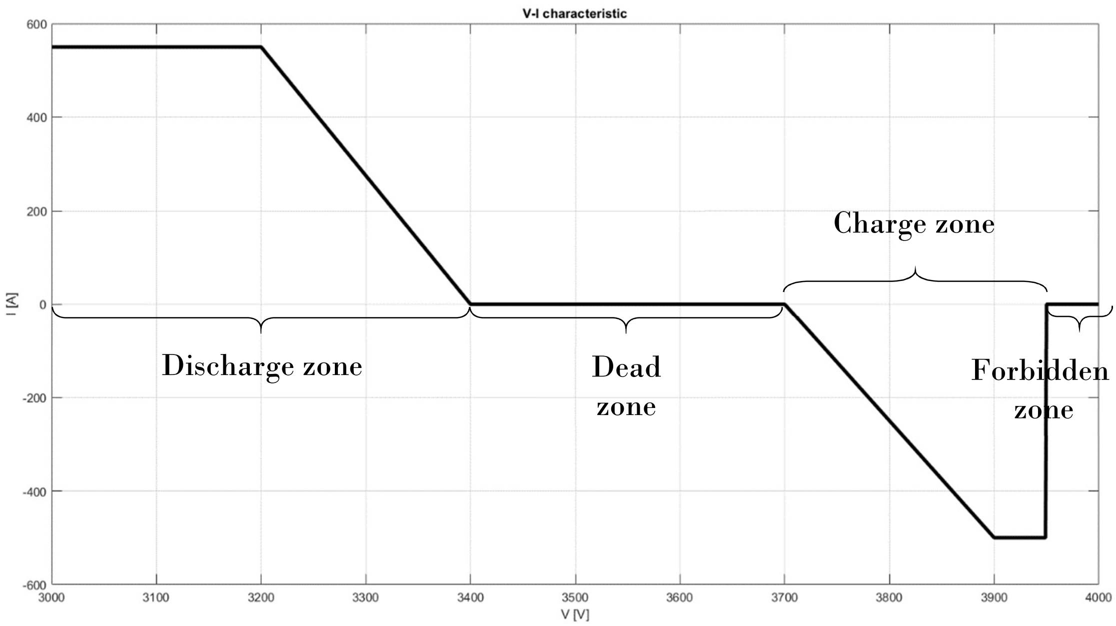

Figure 3.6 Battery V-I characteristic

This Simscape component also takes into account the State of Charge (SoC) level, in order to have a more realistic model, when it decides the current delivered, besides this indicator is one of the outputs, so that it can be monitored during simulation.

Furthermore, if the SoC is below a certain threshold given by the user, if the voltage is in the “Dead zone”, the battery continues absorbing a small current for charging, so that it can support the ESS in case of necessity, even in absence of other regenerative breakings.

Many internal dynamics have been neglected in declaring this component, such as aging, the dependences of voltage from State of Charge or the consequences of high currents in discharging: here the need was to have a control model that allows to see the results that this component could have not only in the quantity of regenerated energy, but also on line voltage, and it was assured by this component.

The value of battery capacity has been taken from [14], where it was analysed the possibility to build new ESS only equipped with batteries, so it can be slightly overestimated, because here the accumulators are always in support of the classical Graetz bridge substation; instead, for what concerns the voltage thresholds, they have been tuned depending on the simulation because they depend on the ESS nominal voltage, but also on the control action that is required

Finally, the “Battery monitoring” subsystem is simply a container for logged signals that such as battery current, voltage, SoC, but also power and energy.

3.1.2 Catenary

The model for the catenary consists of a resistor in series to an inductor, which values depends on the length of the catenary itself; in particular, for railways, the per length resistance and inductance are 0.04Ω/km and 1.4mH/km respectively. For a DC line, like the one here considered, the second element plays a significant role only during transient, when it can create some overshoots in the line voltage, while, at steady state, the voltage drop is due to the resistance effect [16].

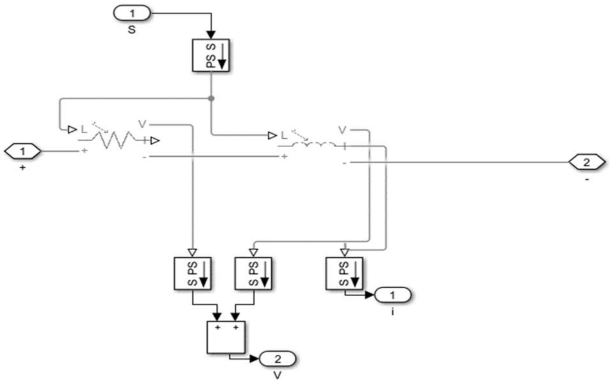

Figure 3.7 Catenary, Simulink realization

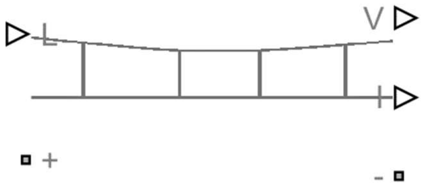

Figure 3.8 Catenary, Simscape realization

For the Simulink model there have been used two components ad hoc declared that have as input the distance (in meters) and, using it, evaluate the corresponding resistance and inductance, given as a parameter the per length resistance and inductance, then the voltage across the two electric components is summed up and translated into a Simulink signal, analogously the current, and are two outputs of the subsystem, as can be seen in *figure 3.7*. *Figure 3.8* represent a more concise way to model the catenary, because it is a single Simscape component which has inside all the mentioned equations.

3.1.3 Train

The train is modelled as a current source which delivers the desired current $I_t = \frac{p_t}{V_t}$, where p_t is the instantaneous train power request for traction and auxiliary functions, while V_t is the pantograph voltage; the reason to model the train as current generator and not as a voltage one is that the line voltage level is primarily defined by the electric substations and not by trains, which only modify it when they absorb or inject power: since when a train is not using energy, it is still subject to the line voltage, but it does not generates or absorbs any current, it was easier transform the power request in an absorbed current instead of in a voltage variation, which should takes into account also the train position, because the pantograph voltage also depends on the distance from the ESS and the corresponding drop due to the catenary, therefore it would be fruitlessly complex, without any significant improvements and with the possibility to have even worse results.

Since there was not in Simscape a controlled current source, a proper block has been declared, with the value of I_t as input, besides it has in output the voltage, so that it can be monitored.

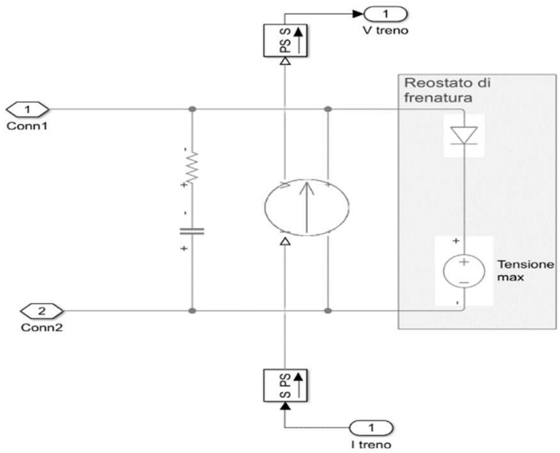

Figure 3.9 Train model

To avoid too high overvoltage in the railway line, when the vehicle is inputting current, trains are usually equipped with braking rheostats that dissipate currents to reduce the pantograph voltage; in the model, this part simply consists on a constant voltage source, whose voltage is the maximum allowable by the train and over which the current is dissipated in the resistor, and in a diode, so that this part can only absorb power without the possibility to deliver it, as in reality (since it is a passive component).

Finally, there is also the train converter filter composed by a resistor and a capacitor (0.1Ω and 3.6mH) [13].

There is also a variant of this model (see *figure 3.10*), which includes, in parallel, a power absorption that consist on a simple controlled current generator which has in input the power itself divided by the pantograph voltage. The memory block is necessary in order to break the algebraic loop, while the rate limiter and the low pass filter placed after the divide block are important to avoid chattering and inconsistent large current values.

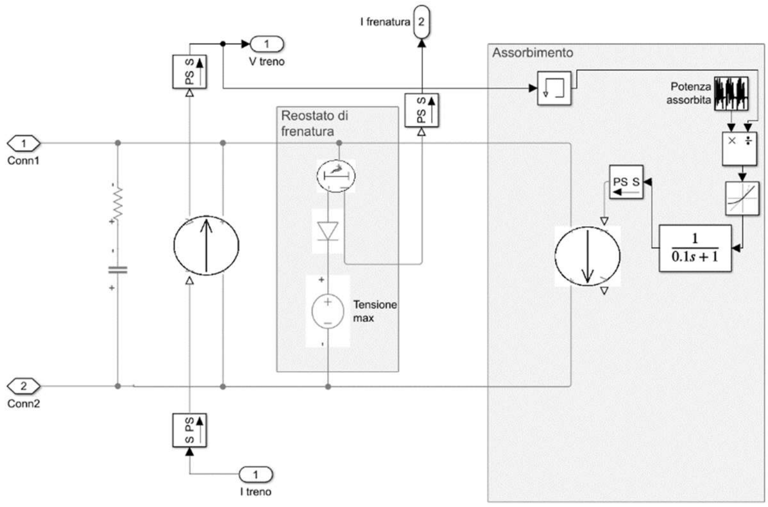

Figure 3.10 Train model with power absorption

This variation, with a constant power absorption, can be useful in case of a simulation of a railways system where other trains are present, in addition to the one of interest, but there are no data available about them, so that they cause variations in line voltage independent from the train current. This case is quite common, because in general there are few data available on the traffic on a specific line, so a solution like this can improve the quality of simulation results. It is also possible to replace the constant power absorption with a varying quantity in presence of data regarding the line situation or it is also possible to have a better approximation with respect to a constant value, using the power values of a train that made the same path in the different direction another day.

From a control point of view, this is a disturbance that make the model closer to the reality.

3.2 Evaluation of system power block

Since the current absorbed and generated by the train is not a datum always available, it has been created a part in the scheme whose aim is to calculate the power needed by the train during its journey, which, combined with the pantograph voltage, can give an estimate of the required current.

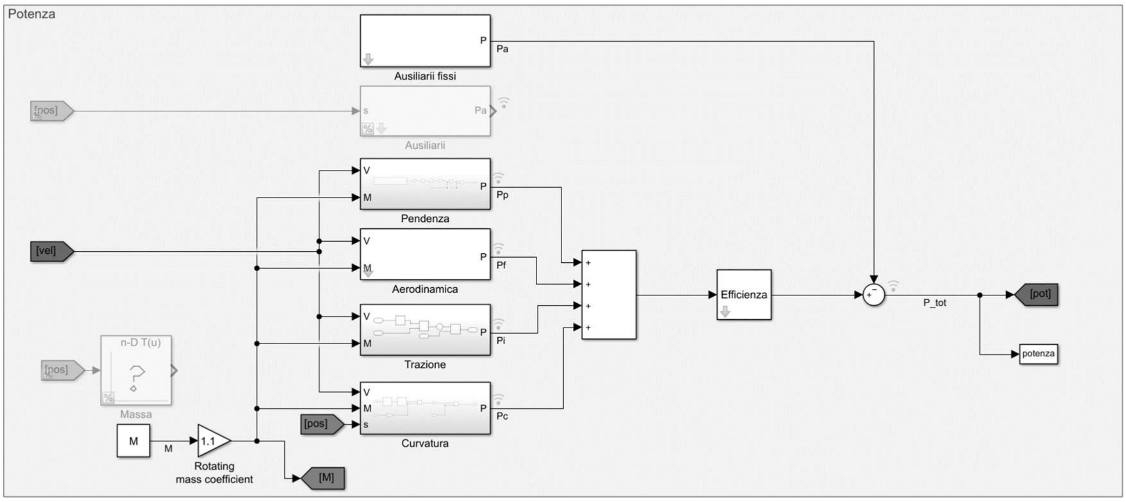

Figure 3.11 Scheme of train power estimation

As can be observed by *figure 3.11*, the total power has been considered as a combination of five main factors: the one necessary for the acceleration, the friction losses (which takes into accounts also the aerodynamics), the declivity, the losses due to curves in the track and the auxiliary power. The first four depend both on velocity and on the train mass, which can be considered as a variable or as a constant; in the first case, it comes from a lookup table that, depending from the position, gives a value: this mimic mass change in every station, as happens in reality, and it can depend from how many passengers are on board and from the number of the coaches and locomotives; all these quantities can be set in an initialization Matlab script, which computes the vector of the overall mass used by Simulink. Instead, it is considered as a constant when the mass variations are negligible with respect to simulation results and it is known only the train mass and not its composition and payload. When the configuration is chosen, the signal arrow is connected to the corresponding label "M", while the other is excluded from the simulation thanks to a "Comment out", in order to avoid problems related to values not declared in the workspace and to speed up the simulation. Just before the label there is a gain whose value is $1.1 = (1 + k_m)$, where $k_m = 0.1$ is the equivalent rotating mass coefficient, because all the powers use this value and not the real mass.

3.2.1 Traction power

The estimation of traction power is based on Newton's law, in particular, the traction force is calculated as $F = M * a$, then it is changed in sign, for the convention used for the current, and multiplied by the velocity to obtain the associated power, as can be seen in *figure 3.12*.

$$P_{traction} = M_{train} * a * v$$

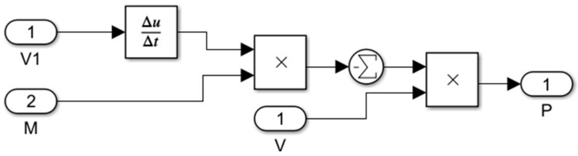

Figure 3.12 Traction power estimation

The acceleration profile could be derived directly deriving the first input, i.e. speed, however if it has some noise or irregularities, it can bring to very great and chattering values, but this is avoided by the velocity controller which limits velocity variations.

3.2.2 Friction power losses

This subsystem considers the power losses due to friction: the way in which this resistance force is evaluated is the one described in *paragraph 2.3.3*, which considers it divided in three different components: aerodynamic, coulombian and dynamic; in these cases, the dependence of power from velocity change, it is third, second and first power respectively:

$$P_f = M_{train} * g * (a * v^2 + b * v + c) * v$$

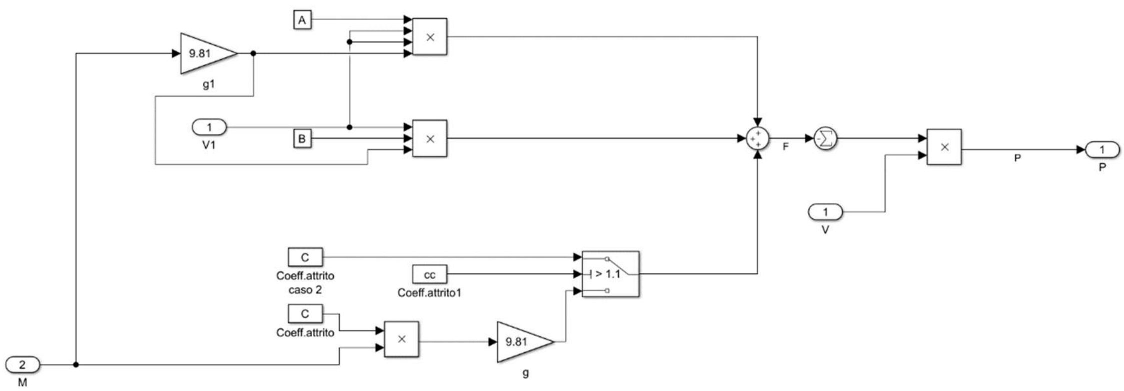

Figure 3.13 Friction losses estimation

In *figure 3.13* it is possible to see how the forces are evaluated, using specific coefficients: for the first one, the coefficient for specific aerodynamic losses is multiplied by the square of velocity and then for the train weight, similarly for the coulombian the coefficient. For the last element there are some differences, whose reason is the possibility for the user to choose, through a mask if he wants to set directly the value of term C or if he prefer to use a dynamic value that compute C using the formula of the dynamic friction (and so the corresponding coefficient must be given as a parameter); for this reason a switch is present. Then the three forces are summed, changed in sign because contrary to motion and multiplied by speed to get the power.

3.2.3 Declivity power

The slope of a route can influence considerably the current absorbed and generated by the train, in fact it can reach the same order of magnitude of the traction power, in some segments, so a good estimation is needed. As can be noted in *figure 3.14*, the angle is calculated from the percent slope, and then the effect of the gravity force which, multiplied by train velocity, gives the power.

$$P_d = M_{train} * g * \sin(atan(s)) * v$$

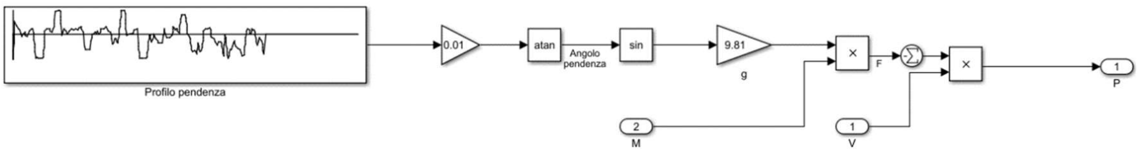

Figure 3.14 Declivity power estimation

3.2.4 Curvature power losses

A train presents some losses proportional to the radius of curvature due to the geometry of the wheelset: is fact the two wheels are integral and with a conical shape and in curve the contact surface is different and so the distance covered. In this way it is possible for the train to follow paths with bends, but some additional friction losses are introduced. A good approximation for these resistances is a proportionality between them and the vehicle weight, through a coefficient ρ which depends on the curvature radius r and is available in table below. Since ρ is expressed in kg/t, it is necessary to divide its value by 1000 inside the corresponding lookup table.

r [m]	200	250	300	400	500	600	700	800	900	1000	1500
ρ [kg/t]	4.2	3.4	2.8	2	1.5	1.2	1	0.8	0.6	0.5	0.1

Table 3.1 Specific curvature resistance coefficients

To obtain the corresponding power, it is only necessary to multiply the force obtained in this way by the actual train velocity, so

$$P_c = M * g * \rho(r) * v$$

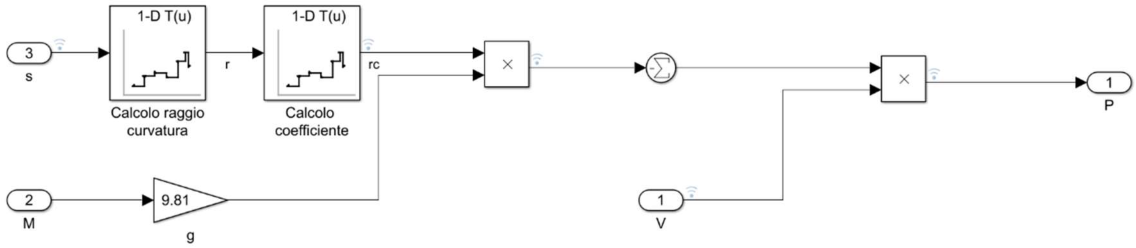

Figure 3.15 Curvature power losses estimation

The subsystem in *figure 3.15* use this formula, in fact it evaluates the radius and the corresponding coefficients through two lookup tables, the second one is the table shown before, while the first one takes in input the distance covered and, based on it, gives the radius in that part of the path, evaluated before starting the simulation by a Matlab script. Then ρ is multiplied by the weight, changed in sign because it is a loss and finally multiplied by the velocity.

3.2.5 Auxiliary power

For the auxiliary power, there are two possible configurations similarly to the mass, one that is simpler, without any inputs and which only consider the number of coaches to decide the power and another more structured. As for the mass, before simulation, the one not used is comment out, while the other connected to the sum block.

In *figure 3.16* it is possible to see the more complete solution: in this subsystem there have been considered all the on-board services of a train, not directly linked with its movements, but necessary for the passenger comfort; in particular here the main elements considered are the ones responsible for temperature control and light services.

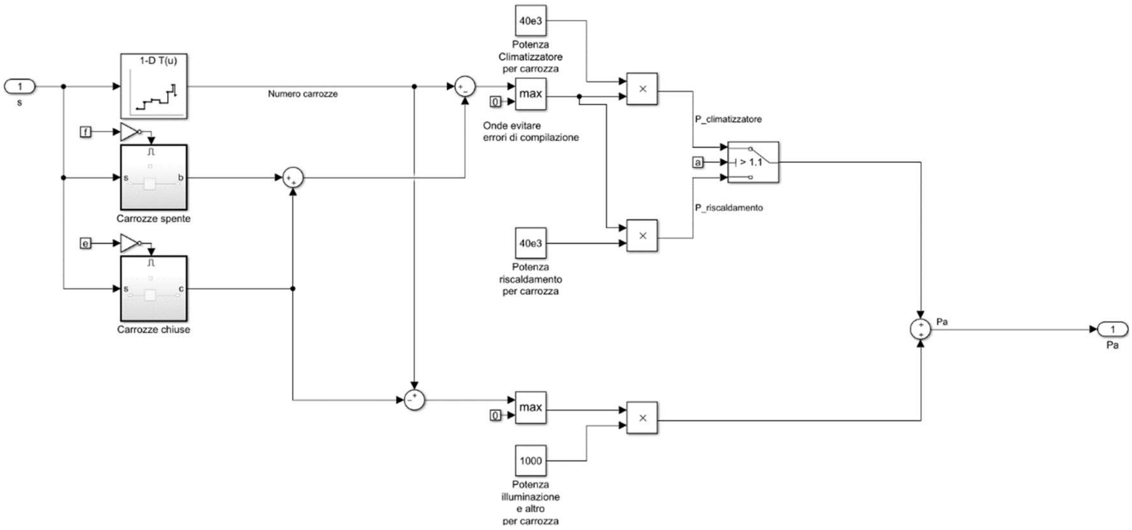

Figure 3.16 Auxiliary power estimation

The user, through a mask, can set if there are some coaches that are closed, so without any temperature control nor light, in order to consider the case of a train in which some wagons are closed to passengers, and if there are some other carriages with temperature control switched off or faulty, besides he can also choose if the system is heating or air-conditioning, because they can have different power requests.

All these possibilities are the reason of the more complex scheme of this subsystem with respect to the others.

3.2.6 *Efficiency box*

All the powers directly linked to train motion also depends on the efficiency of the electric motor, in particular, if it acts as a motor, so $p_t < 0$, the power entering from the catenary must be greater, precisely $p_c = \frac{p_t}{\eta_t}$, while, if it acts as a generator ($p_t >$

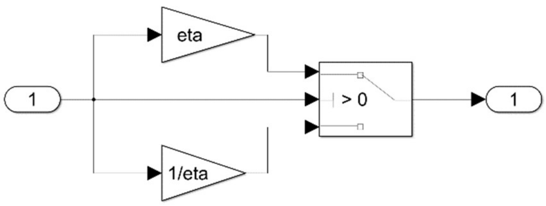

Figure 3.17 Efficiency subsystem

0), the generated power seen by the railway line will be $p_c = p_t * \eta_t$, as can be noticed in *figure 3.17*.

3.3 Train position

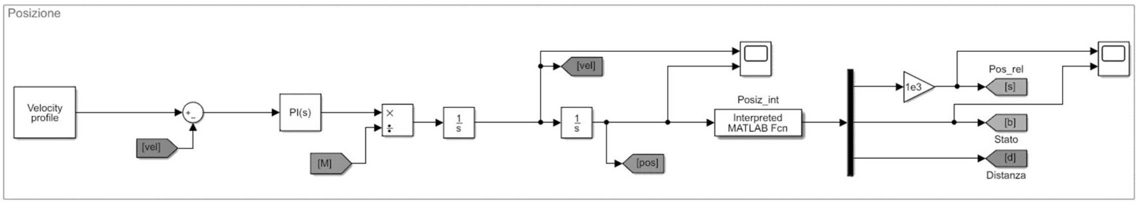

Figure 3.18 Position estimation

The model needs the velocity profile of the train to estimate its absolute position: the PI controller mimic the pilot role, in fact it takes the desired velocity profile and give the needed torque to obtain it evaluated through a feedback control, then it is passed to the mechanical transfer function (that is simply $F(s) = \frac{1}{M*s}$, where M, train mass, is given in this way in order to allow variations during simulation) which give in output the real velocity, then an integrator evaluates the position. After this, some other data, deducible from this quantity, are necessary and are calculated from a Matlab function: they are the relative position of the train with respect to the last electric substation that it has passed, a Boolean signal that tells if in the segment where is the train there are two or one substations (necessary to choose the proper electrical scheme of simulation), and the distance between the two ESS (in case of a tract with a single substation, it is the space between the start and the first one or infinite, if the train is near the end of the line).

3.4 Railway system complete model

The next step, after having created the previous components, is to assembly them and create a model of the railway system: a key characteristic that it must have is the possibility to be used in very different conditions and the modularity, which improves the readability and the usability. The idea is to identify the two situations in which the train can be, that is sustained by one or two ESS, and use this information in the simulation. The overall model so will consist in two main parts, one simulating the train in a line with one ESS and one with two, then an internal logic should decide at each time instant which set of data of the two consider.

The information about the number of substation is taken from the position and, in particular, from the second output of the interpreted Matlab function explained in *section 3.3*; of course, the Matlab function must mirror the real ESS disposition in that railway segment to be as precise as possible. Then, using the other two outputs, the distances of the train are found and so the catenary values calculated. The model described consider the presence of a single train on the line, other possible vehicles enter as a disturbance in the train component, because this simplifies the scheme very much, since there is only one element moving on the line with the corresponding simplifications in distance calculations and above all, there are no intersections between trains, which are not easy to handle. However, it is also possible to simulate the presence of two vehicles in the same line, but considering only that specific section, but this is not a real problem, because the coupling effects are relevant only if they are both fed by the same ESS.

The variables of interest are sent to scopes and to workspace in order to be utilized.

The two subcases, will be explored in the following.

3.4.1 Case with 1 ESS

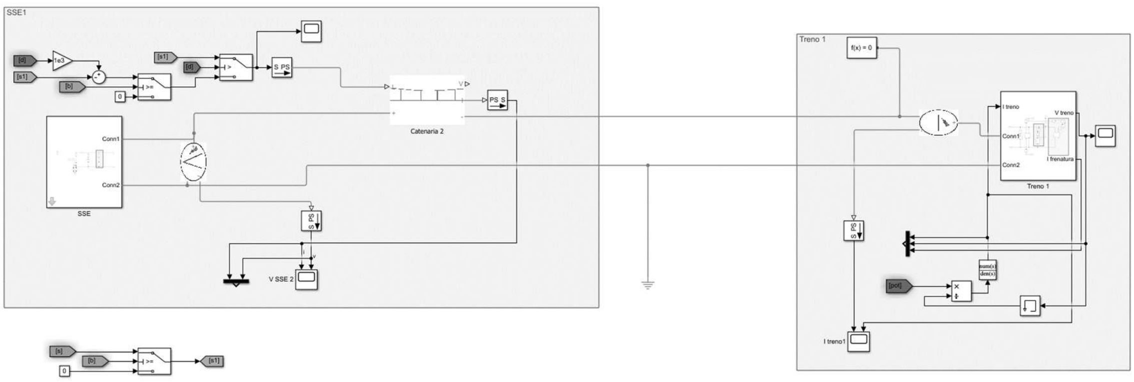

Figure 3.19 Case with single SSE

Looking at *figure* 3.*19* it is possible to notice the ESS on the left, and the train on the right in the other area.

The ESS component is connected to the equivalent electric circuit and a sensor in parallel to it measures the instantaneous substation voltage. Then the signal is translated into a Simulink one and sent outside to the manager logic. This small block has been ad hoc declared as a Simscape component, using the same logic of a real voltmeter: it has a high resistance and measures the voltage on it.

Between the ESS and the train there is the catenary that also measures the current flowing through it and the voltage drop; its input is quite complex, so a few words are needed. First of all, a switch placed under the substation area decide the relative position depending on the state, in particular, if it is the case with a single substation, the space is the relative position evaluated using the train movements data, otherwise it is set to zero because the simulation does not interest this case and so doing the calculation time is partially reduced. Then, if there is not another substation after the last passed, so the distance from the next one is infinite, the catenary length is the relative position itself; in the contrary case, it is the distance between the start and the first ESS minus the path already covered.

For what concerns the train part, there is the dedicated block connected to the circuit and to a current sensor, whose basic idea is similar to the voltage one, that measure the actual train current. In input the subsystem has the desired current evaluated dividing the requested power by the pantograph voltage, $I_t = \frac{p_t}{V_t}$; a low pass filter avoid problems related to excessively fast changes due to calculations and not present in the reality, while a memory block in the voltage signal line breaks the algebraic loop simplifying the simulation. Then the measured voltage, current and breaking current (the one that is dissipated on on-board rheostats) are sent to the manager logic which decides if they are data of interest or not.

A ground component and a solver configuration complete the circuit.

3.4.2 Case with 2 ESS

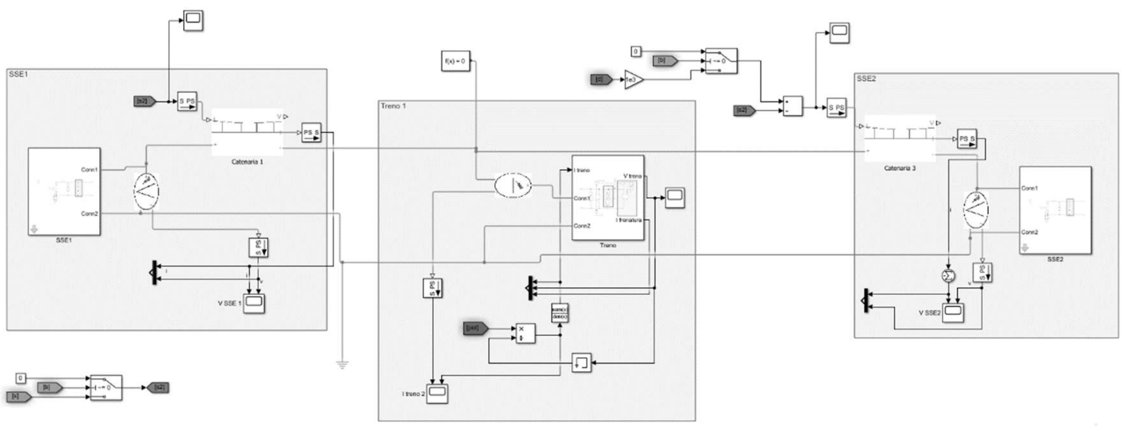

Figure 3.20 Case with 2 ESS

It is similar to the previous one, of course here there are two areas for the ESS and so there will be electric data for both of them.

For what concerns the train, it is exactly the same of the one in the last case, the main difference is on the catenaries lengths, in fact for the first one it is simply the relative position of the train, while for the second, it is the distance between the two minus the covered path.

3.4.3 Manager logic

The manager logic is quite simple and simply consists in some switches, if the state, with label ‘b’, is 1 (so the case with a single ESS), the data regarding the train and the first substation are the ones coming from the corresponding case, while for the second ESS it is always zero, since it is not present; on the contrary, if the state is 0, the data to show are the ones coming from the second case. Then the signal from the switches are sent to scopes and to workspace in order to have the possibility to manipulate them.

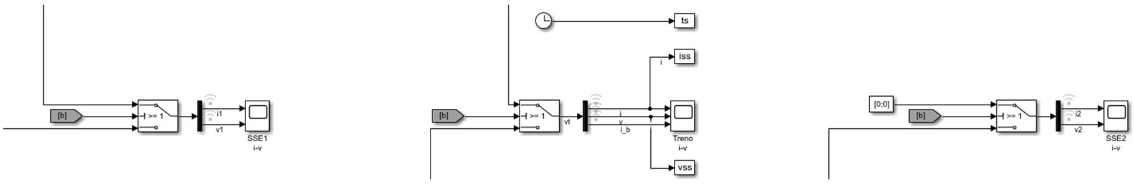

Figure 3.21 Manager logic

3.5 Model reusability

The reusability of this model is quite high, thanks to its flexibility, which has been a key characteristic in the choice of the library to use, Simscape, instead of Simpower System or a simple block-oriented model, in fact it allows to declare new components, similarly to OpenModelica. Moreover, the modularity that stays at the base of this model allows to use it for the simulation of different lines with the necessity to act only on the Matlab function used by Train Position subsystem to establish the relative positions, in fact, when a new path must be simulated, if there are no changes in train or ESS technology, it is only required to change inside the Matlab function the electric substation disposition and then the model could be run.

3.5.1 Evaluation of different train configurations

In all these simulations it was supposed that the train was an ETR 500, because it is the model on which the measuring systems are installed, however it is also possible to use it also to simulate the behaviour of another train without difficulties, in fact it is only required to change some parameters in power calculation area. The most significative changes are the specific friction coefficients and the mass, which can also vary using the same train in different configurations; in case it has been calculated using the script that consider the variations happened in every station, it is required to change to locomotive and coach mass values.

The model could also be used for freight trains, in this case if the mass is not insert directly maybe it may be necessary to set different wagon masses inside the script for each typology that is present in the vehicle, moreover the payload cannot be evaluated using approximative estimation, but should be precise because of the percentage of the total mass due to it is preponderant.

Furthermore, in this case, considering that the total train length is significant with respect to the segment one (if the segment length is $l_s = 20km$ and the train one $l_{train} = 1.5km$, the ratio is 7.5%) and that the locomotives may be more than one and distributed along the vehicle (on its extremities, in the boundary case), it could be considered two distances from substations for catenary: the one from the back locomotive and from the head one; in addition there will be a segment of catenary of constant length between the two traction locomotives. This will also bring the possibility for a train to be contemporary in two segments, which can be considered as a third case. In addition, there could arise some difficulties in evaluating the declivity power and the total power should be shared between the locomotives. Anyway, these are all refinement that can be significative only in case of very long convoys, and only in that case should be considered, to avoid useless computation time increases: for example, the mentioned third case, it is not significative for a short train, because both the locomotives are close to the ESS, so the voltage will be the nominal one or less different, while for what concerns the power, and so the current, it is mostly supplied by the closer substation and the contribution of the other two is negligible, so it does not interest if the resting small percentage comes from one or two ESS.

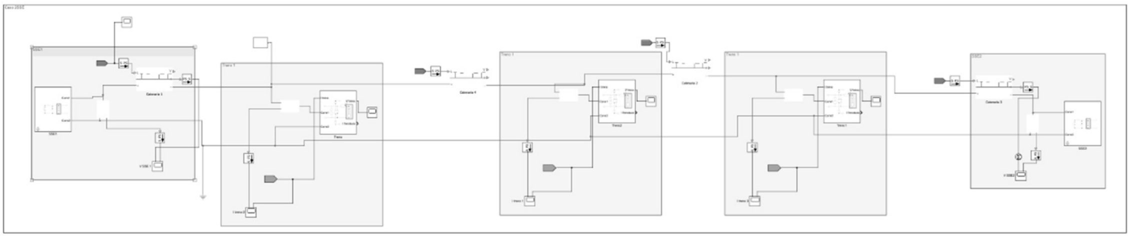

Figure 3.22 Case with three trains on the same segment

There is also the possibility, as already mentioned, to insert more than one train in the same segment: in this case, it would be firstly necessary to have a position and a power calculation subsystem for each convoy, then it should be evaluated the length of each catenary section. For example, in *figure 3.22* is shown a case with three trains, two moving in the same direction and one in the opposite. The distance between trains and substation is evaluated taking into account their displacement, summing or subtracting it depending on the direction. The most difficult thing to manage is the intersection between trains and when they exit from the segment. In the first case, when happen, the two trains are exchanged, in other words, the power label that determines the absorbed current and the one that regulates the catenary length are swapped through a system of switches. Of course, only trains in opposite directions can intersect, apart from if it is clearly specified that there are four or more rails. In the second case, when the distance of the nearest train from the electric substation becomes a negative value, still through a switch system, the train power is set to zero and also the distance between it and the train in the middle, whose distance from ESS is used to compute catenary length. Since here the trains are all explicitly modelled, it would not be necessary to add external power absorptions.

3.5.2 Substation and catenary configuration changes

In this case is even easier to handle a change, in fact the only changes are in parameters. Starting from the catenary, it might be necessary to modify its resistance and inductance values, because it is made in another material or the technology could be different, for example if the model is used to simulate a train powered through a third rail: in this case the resistance level varies significantly and must be modified.

For what concerns electric substations, some changes have been done also during the following simulation, like acting on its voltage output: in this case, the voltage source parameter or input, depending from the type, must be modified, but also the filter and train capacitors initialization voltage would require the same action, although this is not strictly necessary, because it affects only the very first time instants.

It is also possible to model an entire path with its substations, without partitioning it in the two subcases (one or two ESS). In this case the hypothesis that the power absorbed in a segment entirely come from the border substation is not necessary because all the substation in the model have a univocal correspondence in reality and are all present in the model.

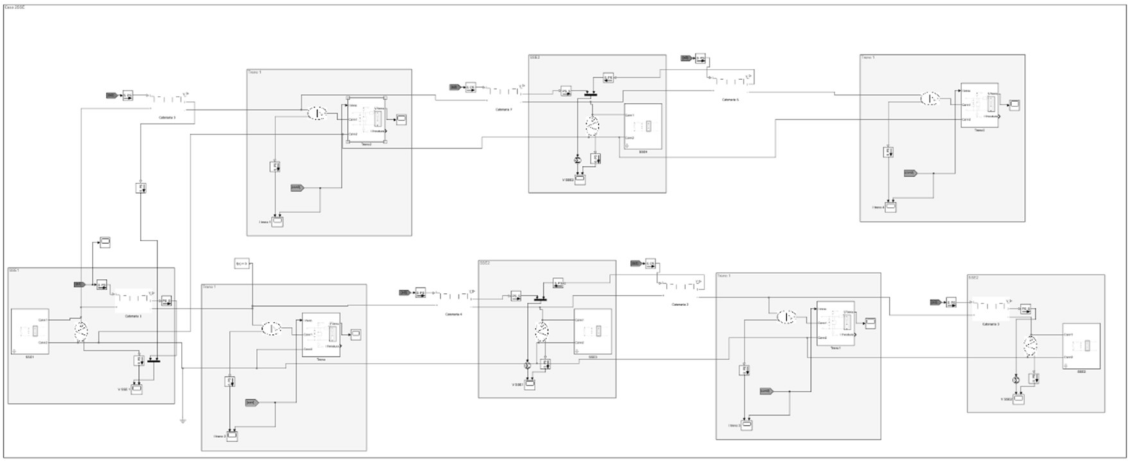

Figure 3.23 Case of a path with 4 segments

In *figure 3.23* can be observed an extended model of a path composed by four segments, one supported only by a single substation: this is only an example and it may also be possible to model a round circuit with the first and the last ESS connected together. In this case, the substation current must be taken on both of its side, because it could have two directions. In each segment there is a train component, but it will be active only the one corresponding to the real train position: this is done with a switch system analogous to the one used to manage multiple trains. With this solution it is possible a deeper and wider study of energy flows, because it is inspected considering all the possible sources, however it is important to remember that it drastically affects the computational time protracting it.

A possible usage of this solution is to simulate the effects that can have the installation of a stand-alone battery station in a still operating railway network, because these kind of substations, as will be analysed in *section 4.2*, are only a support for the powering of a section, so the model will have both the ESS and a stand-alone battery station in the middle, in addition to trains, one for each subsection.

Finally, it is also possible to insert more trains in the case in *figure 3.23*, to simulate the complete path in all its complexity, in this case the number of trains in each segment should be equal to the number of circulating convoys, because, in the worst case they can all be in the same segment, however, if there is a smart managing logic, this could be considered in deciding the amount of trains per segment. Anyway, the model complexity increases dramatically, not only in the object-oriented part, but also in the block-oriented that decides the active vehicles and their distances, so this should be done only in case strictly necessity, because the improvements are marginal with respect to the standard model.

3.5.3 Transition from DC to AC traction

This model could also be modified to simulate an *AC/AV* railway, in case of necessity. The transformation is not easy like the modification debated before, it is much more challenging, in fact some new components must be created and other adapted, because the model was done for DC traction.

The first change regards the catenary that will be slightly modified due to the different material of composition, which affects the resistance and inductance values, moreover it should be also considered that now there are two contact wires, which can cause some coupling effects, besides the equivalent inductor for an AC line is always significative in the final result, not only during transients as happens for a DC railway. For what concerns the feeders, their modelling depends from the level of precision that is wanted to be reached, and is linked to how the Double Parallel Places are modelled; in fact it is possible to use for them autotransformers as in reality, and so the presence of feeders is necessary, although it is even possible to consider the feeder as a constant monophase voltage generator, while if the DPP are simply represented as sources, feeders are useless.

The train model should not have great modifications, the absorbed current will be lower, but this is done automatically by the way in which it is evaluated, which consider the required power and the pantograph voltage, that now is not almost constant, but in AC.

The part that mostly required modification is the one that regards the power supply: new components must be declared, in particular Double Parallel Places, even others if the required level of complexity is higher. The electric substation component will be significantly changed, first of all in its internal filters, which are different from the one of a DC ESS, but especially in the power source, because now is AC: it could be modelled as a monophase voltage source that generates 2x25kV at 50Hz, similarly to what done for the DC scheme, otherwise it is also possible to create a model closer to the real substation using a transformer with the national grid, a triphase voltage source, on primary side. This solution for an AC substation is more practicable with respect to a DC one, because the transformer is easier than a Graetz bridge and so the corresponding calculations, therefore the total computational time will not increase too much, therefore it allows also to simulate the reversible power flow, from catenary to the grid, which is possible for AC lines, in theory; however it is important to constantly have in mind if a simpler modelling could not solve the problem in a good manner for the simulation purposes.

Furthermore, if the feeders are required in the model, it is also necessary to insert in the electric substation component a voltage source that supply them, analogous to the one used for the contact wire.

The next step is to create a new component for Double Parallel Places, as already mentioned it could be simply a voltage generator, solution which avoid the need of feeders; however, in this case, it would be better to use autotransformers in modelling, because DPP only support the line, they do not supply the cell entirely, part of the energy comes from the substation, in fact the apparent power of their transformers is 15MVA while for ESS was 60MVA, much greater because they supply all the half-segment, therefore the solution would be more exact, or better less subject to restrictive hypotheses, using this modelling strategy. Then, inside DPP there should be a switch which model the neutral section: since the length of the segment involved by the NS is limited with respect to the section, and the problems that it can create are further reduced by the last building strategies, it is possible to apply the same hypothesis used for the train, so to consider negligible the neutral section length with respect to the section one and to model it as a simple switch that divides the two subsection, when open.

At this point it is possible to realize the entire model in a modality similar to the DC one, i.e. a modular model, which allows simulations of paths of arbitrary length without the need of univocal correspondences between real and model components, and consequently without representing the entire line in the model, which increase its readability and usability.

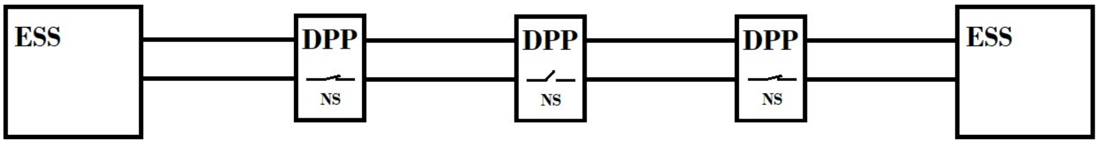

Figure 3.24 AC/AV general scheme

The general scheme for the model is shown is *figure 3.24*, and it could be observed that it is a bit more complex than the DC one, because now there is also the cell subdivision and in each cell there should be placed a train model; of course, the only activated component will be the one in the cell where the train is, while the other remains passive, detached from the line.

The cell subdivision increase the model complexity, however, thanks to the fact that the electric substations supply only an half-section, there is no necessity to have two separate cases for a section supported by one or two ESS, in fact if there is only one ESS, it is like being in a general subsection, without any other difference, therefore, if this happens at the beginning of the line, the starting active cell will be the third or the fourth form the left, depending from the initial distance from the substation, while if it is at the end of the line, there should be no problems because the active train component will be automatically the one in the first and then in the second cell.

It could be made a modification of the Matlab function that manages the relative positions, inserting also the progressive distances from the Double Parallel Places, so that it may have an output that declare what is the active cell and the distance from it directly, without doing additional computations using Simulink blocks. This is not strictly necessary, however it simplify the computations and increase the model readability, furthermore it allows to consider also the fact that the distance between DPP is not always the same, but have some variations.

4 Recovery strategies

The efficiency improvement is a very promising field, in fact more than 30% of traction energy is generally wasted in breaking [17]; for this reason, some solutions for reusing the energy otherwise lost have been proposed and have been under study by several research teams for many years. There are articles related to this topic published in the first 80s [6], [18], and this reveal its importance for railways enhancements. Nowadays, at least in the general case, the regenerated energy is partially used for auxiliary services, then the rest is sent back to the catenary only in case of another train is accelerating close to the braking one, otherwise the line voltage increases until it reaches the protection rheostat threshold and it is wasted [19].

There is not a unique or a best solution, but, on the contrary, there are many, each one with its advantages and disadvantages, so that in taking a decision it is better to firstly study the field of application, i.e. the characteristics of the rail network, and then, after a simulation that confirm the choice, apply the most suitable solution. A common situation is the presence of different technology in the same network, (e.g. see [20]), both for convenience reason and because the various solutions might have been implemented in different times.

The adoption of one of the actual possible solutions can bring to the removal or the reduction of on board rheostats with a consequent lightening and further reduction of the heat production, which determines additional energy savings particularly in tunnels, where it is possible to reduce the use of cooling and ventilating systems. But above all, it reduces the carbon footprint due to transport, with the consequent reduction of costs for energy purchase.

Since the application of such technologies has its own cost, it is better to carry out a preliminary investigation about the convenience of it, because the recoverable energy depends on the train service, the distance between successive stops, the slope of the track, the number of circulating trains. Besides, in addition to the regenerable energy, it should be considered where it flows, because if it is mostly absorbed by near accelerating trains, it could be not so efficient to make a storage system (a study in this sense has been carried out by Alstom [21]). Some Simulink schemes are already available to simulate the behaviour of the railway lines and of the train, considering the different factors listed above, to verify the impact that the adoption of one or more of the studied solution can have and help in taking a decision.

In order to have a general overview, in the following there is a brief exposition of the actual main solutions.

4.1 On-board storage

A direction that can be followed is based on an on-board storage system, which can use different technologies: batteries (of different technologies) and super-capacitors or a combination of the two. There are also some applications of flywheel, in New York and Hong Kong subways, but they are not a suitable solution [17], so they are only mentioned.

Super-capacitors are appreciated for their high power density and for a longer lifetime, on the other hand they are usually more expensive than batteries. They are particularly indicated for power intensive cases, paths with many stops and accelerations, because they can absorb and deliver high currents without problems.

Batteries have the advantage of a higher energy density but can absorb lower powers with respect to a super-capacitor, so they are indicated for situation in which there are long regenerative brakes with a low intensity, as in the case of a slope. However, even inside battery field, there is a multiple choice, because there are different possibilities, with their advantages and disadvantages, for example in Japan are used both Li-ion and Ni.MH [22]. Hybrid solutions mixed the pros of the two solutions: when the train is in regenerative braking, the energy is used to charge the super-capacitor, till its State of Charge (SoC) is inside the control limits, then part of the energy is used to charge the battery and the rest, if present, is dissipated in rheostats [17].

An interesting usage of this technology is for non-electrified railways, in substitution to diesel locomotives: the train store energy when it is in an electrified tract, and when it is breaking; then use it when it cannot be fed by the catenary [23]. Another possibility, for non-electrified railways with a short distance (less than 2km) between two consecutive stations is to use capacitors that are charged with a high current during its stays, which assure to reach the following stop [24].

The main disadvantage of this solution is the weight and space occupation. In fact, the presence of accumulator reduces the space available for passengers and, at the same time, increase a lot the mass of the train, which brings to an increase of energy demand. For this reason, if the chosen strategy is on-board storage, it is wise to check what of the three configurations is the best one; for example, a battery, to guarantee the same power absorption of a capacitor, will have a quadruple mass, and could store a very great amount of energy: if the field of application is an electrified train, maybe it is better a super-capacitor, if it is a non-electrified inter-city rail, this one could be a good solution. Another situation in which an on-board storage is a good solution is for railways with a significant number of accelerations and decelerations but with a low traffic, so that acting on the electrical substations will not be convenient.

4.2 Electrical substations storage

Another possibility for the use of accumulators to recover regenerated energy is to place them not on the train, but in an existing electrical substation or even in a stand-alone ESS: so doing, the problems related to mass increase and passenger space reduction are overcome, besides it is not necessary to act on the trains so it is possible to use the circulating ones, without any modifications. On the other hand, they can only recover the energy coming from train passing in the tract which is powered by them, so an optimization study for substation placement should be carried on.

There are studies [13], [15] for the application of this solution to regional and sub-urbans trains because, even though they are not so frequent, the number of stops, and so the breaking energy, is quite considerable. An important item is to find the correct site where the equipment will be installed, considering the initial costs (it is more affordable to place it inside a still existing substation with respect to build a new one) but also the distance from the points in which energy is generated, to avoid energy loss in the catenary; moreover, even the technology to use should be analysed, so the problem is not so banal.

Another possible use of an auxiliary battery station is to strengthen the existing railway network, in fact the traffic increase of the last years and the use of high-speed/high-capacity trains on the existing 3kV line can cause problems in power absorption and losses [14]. A natural solution should be to build some new ESS to support the line voltage, however this is not always possible, because the medium or high voltage grid may not reach the chosen place, so an alternative is needed and is an Alone Battery Station (ABS). Briefly, it supports the absorbed peak current when the high performance train is accelerating giving a power higher than the one that a normal ESS can supply; so doing the stand alone substation reduce the voltage drops on the line and the ESS current peaks (there can be even an halving of them), as can be noted in *figures 4.1, 4.2*, taken from the paper.

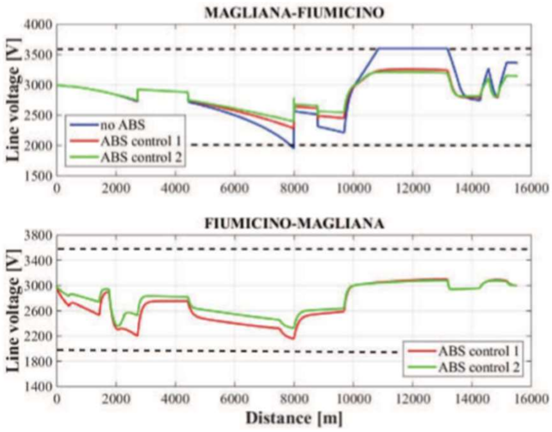

Figure 4.1 Voltage results of application of ABS

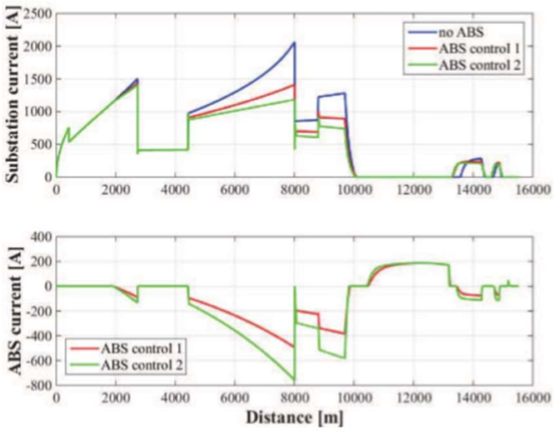

Figure 4.2 Current results of application of ABS

Even if there is an efficiency increase, this is not the main goal of this strategy, but it is a pleasant secondary effect, because these ABS use the breaking energy to charge increasing the overall efficiency. The logic that manage the battery decides when supporting the line through a voltage threshold and a constant SoC monitoring. In fact, when it reaches a minimum level, the controller waits for no other utilizers on the line and absorbs a low current to charge the batteries until an intermediate level, so that the ABS could both support the line and absorb a peak of current.

4.3 Reversible substations

For some aspect, this solution is the most natural one: if the train is consuming, the ESS provides energy from the public grid, while if it is regenerating, the ESS transfer the exceeding energy to the grid; for this reason, this issue has been studied for many years (see [6]). However nowadays it has reached a new importance because the needed power electronics is much more affordable than in past years, furthermore now it can more easily manage even great power flows.

This solution is based on an IGBT inverter and a thyristor rectifier supervised by a switching controller: the rectifier acts in traction mode, while the inverter in braking one and are both controlled dynamically by a single controller that switches between them depending on the modality. The rectifier and the inverter are two separate groups, to avoid a continuous inversion in the connection when the voltage sign change, besides the traction power is usually greater than the regenerated one, so for a cost reduction, the sizing of the two components is different; moreover in some cases, in order to have a greater robustness of the substation, the IGBT converter is in parallel with a diode rectifier.

The main advantages of a reversible ESS are:

- The possibility to have a bidirectional power flow, which allows an improvement of efficiency, because it regenerate over the 99% of breaking energy [21], with the possibility of a total removal of on-board rheostats;
- The reduction of harmonic pollution caused by traditional Graetz bridge substations, which, for this reason, need additional filters to have a power factor acceptable for the limits imposed by the grid operator [10]. In fact, a reversible substation which uses force-commutated converters absorbs almost only active power, besides it is possible to balance the power between adjacent substation to avoid overloads and to better control the line voltage [9].

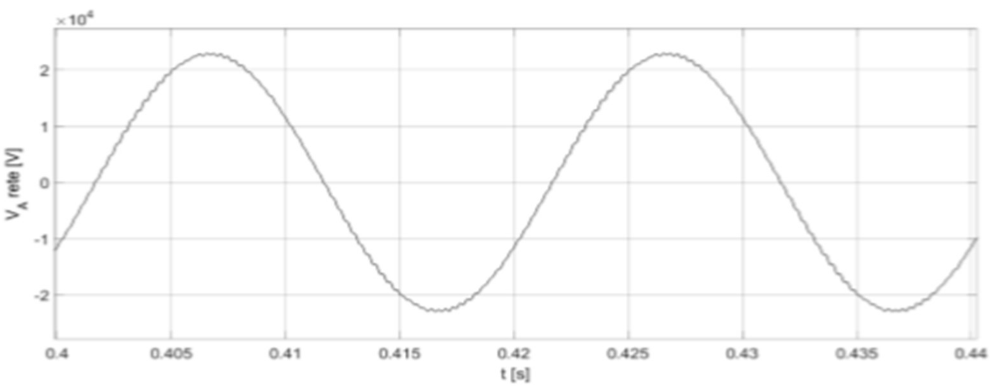

Figure 4.3 Phase voltage on primary side of a reversible substation with a passive load

Analysing the current absorbed or delivered by the ESS, shown in *figure 4.3*, it is possible to note that they are almost sinusoidal, the only present harmonics are at high frequency, in the band at which the converter operates, moreover there are some practices to further reduce them;

- The regulation of its output voltage, which can bring to a further reduction of losses, increasing the energy regenerated by trains distant from the ESS and which permits to maintain a constant DC voltage, or to decrease its variations (whose amplitude also depends on the PI tuning), on the catenary even in presence of an absorption or injection of energy; this is an important issue because power motor drives are much more affected by distortions and variations than electromechanical ones, furthermore, some special actions like de-icing are possible, giving a little different voltage between two subsequent ESS, so that a small current flows in the catenary, even in absence of trains and heats it. Another advantage is linked to the fact that modern trains absorbs much more energy, because have more auxiliary services and can guarantee higher accelerations, furthermore many ESS in urban and suburban areas are connected to Medium Voltage (MV) grid instead of High Voltage (HV) for a cost reduction in materials and components used in the substation and because the MV network is more diffused inside a city than the HV one and an extension of it could be difficult to carry on. For all these reasons, it may be necessary to limit the maximum power absorption in order to avoid exceeding the allowable thresholds.

On the other hand, there are also some drawbacks, with respect to Graetz bridge substations; in fact, they need a control system to guarantee the performances listed above and this factor, coupled with a more complex structure which brings to a lower reliability. Moreover, a conventional ESS can support more easily an overload with respect to a reversible one and it is less expensive [16].

The result in terms of efficiency is an annual energy saving of 18%, from an ALSTOM simulation on a test track in La Rochelle 14km long and with a catenary voltage of 750V (some other tests will be carried on with higher voltages vehicles), so a considerable reduction which can justify even economically an investment in a structure like this, without considering all the other listed benefits that it brings.

4.4 Smart grid implementation

A possible use for regenerative breaking energy is to reuse it inside a smart grid which includes also a railway station [25]. Its services like air conditioning, elevators, lighting, ventilation, heating and so on are powered by a smart grid; in order to better use the energy coming from the train, an energy storage system is used: the peak of current is employed to charge it and then used for the services. If the SoC is too low, it is charged using the public grid, the logic is not so different from the one of a stand-alone battery substation, but here the utilizer is not the train and the railway network, but its supporting infrastructure. Moreover, it is possible to add other sources of energy like photovoltaic panels or wind turbines, to decrease the dependence from the external grid.

There are also studies [5] for a wider configuration: the smart grid include a whole railway network, but it is divided in some further sub-grids with a central control centre which decide a plan to optimize energy consumption, power demand (with the aim to reduce it, especially in power peaks which have an impact on the electricity network capacity, in order to avoid penalties) and costs.

The subdivision scheme is visible in *figure 4.4*.

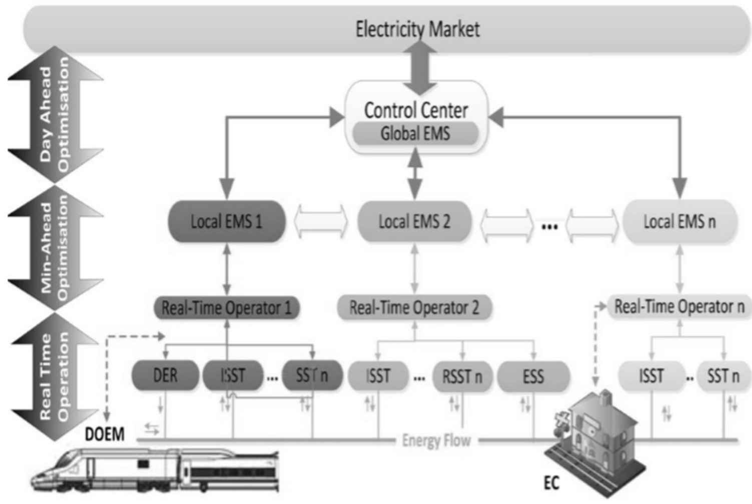

Figure 4.4 Smart grid subdivision

The idea under consumption optimization is that the energy regenerated or saved in the smart grid reduces the demand from the national grid. The subdivision is necessary to simplify the control problem, because it decreases the system complexity and dimension; moreover, some of the loads and generators, the trains, move inside the network and it is easy to manage them in a subnetwork where they are in or out or with a relative position, instead of in the global one. However, each sub-grid is in contact not only with the public grid, but also with its neighbouring subnetworks, to have a better coordination, particularly in power demands at their limits, in applying the optimization plan received by the central control centre. In order to do this, in each sub-grid there is an intelligent substation that communicates with all the components acting in the subnetwork to make them apply the plan giving commands. These components can be very different, they are substation connected with the public grid (both in unidirectional and bidirectional way), but also storage systems, renewable sources, trains (through their Dynamic on-board energy manager), stations and other services in the railway network.

5 Validation

The trains under exams are all equipped with a MVB system that acquires data from the vehicle logic and allows to monitor it, especially from an energetic point of view. These data are all coded, most of them are states, for examples there are flags which register the traction state, the interval where the line voltage is included, the state of some switches (on or off) or of the pantograph, and many others; however, there are also the geographical coordinates and some electrical quantity related to the train. Unfortunately, these are internal data for the train usage, so there can be some problems in the correct interpretation for an external usage.

Now there are also other available data from another system, EMS, equipping experimentally on two locomotives, which measures the current and voltage at the pantograph, so the ones that enters in the machine; moreover it collects other information of interest such as position, velocity, which can be useful to validate the Simulink model, and validation is a necessary step before any use of it, to guarantee the reliability of the results. However, first of all, it is better to make a rapid analysis of the data coming from the two measuring system, of course of the ones that are comparable, to check if there is a good correspondence.

5.1 Data comparison

The comparison between the two sets of data will be on four different variables: the two GPS coordinates, latitude and longitude, will be used also for the synchronization of time, then also the line voltage and the actual velocities will be compared. The current has not been compared because the one of MVB is not the current entering from the pantograph, but an internal current, so there could not be any significative correspondence.

In comparison, it is important to consider that the MVB data are acquired about every second, while the EMS every minutes, therefore they are less and the curves have less variations, moreover, sometimes the signal is lost, this happens with a higher frequency for MVB, so the graphs simply interpolate the trajectory between the two closer points, but that segment is meaningless (however, it is easy to note).

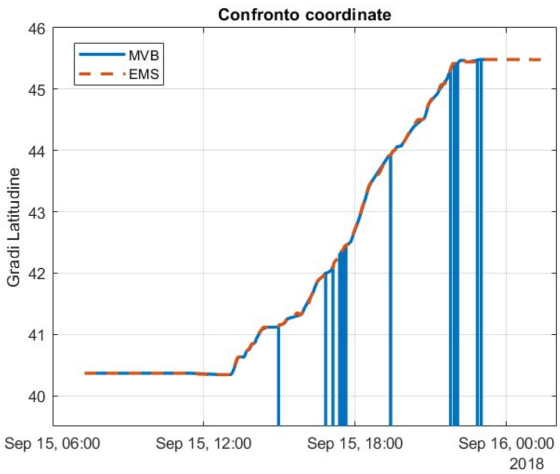

Figure 5.1 Latitude comparison

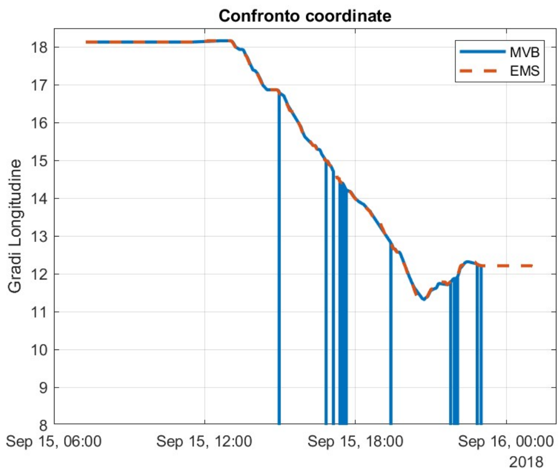

Figure 5.2 Longitude comparison

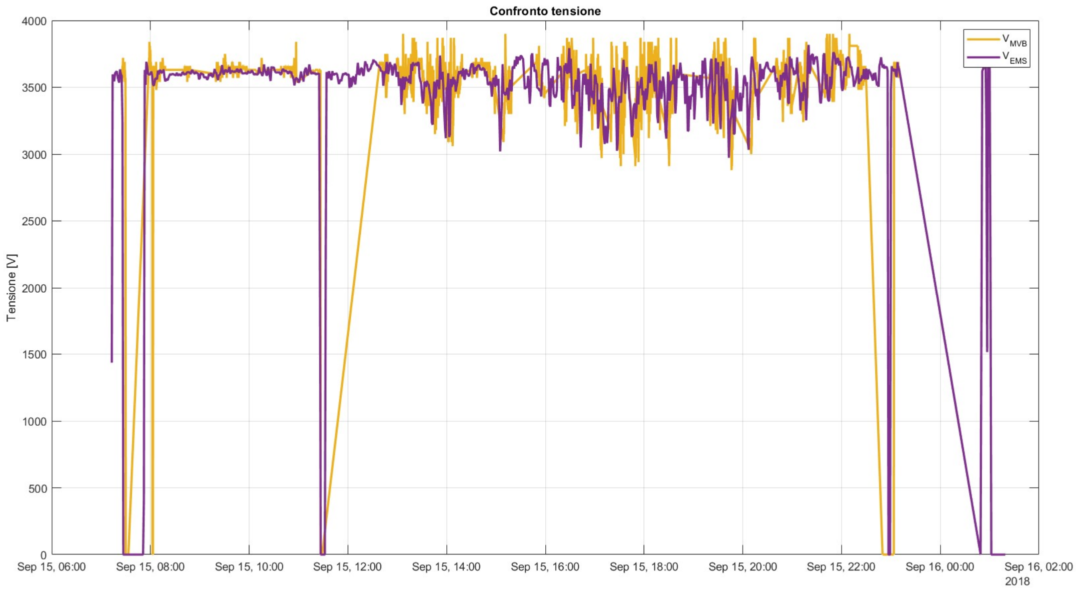

Figure 5.3 Voltage comparison

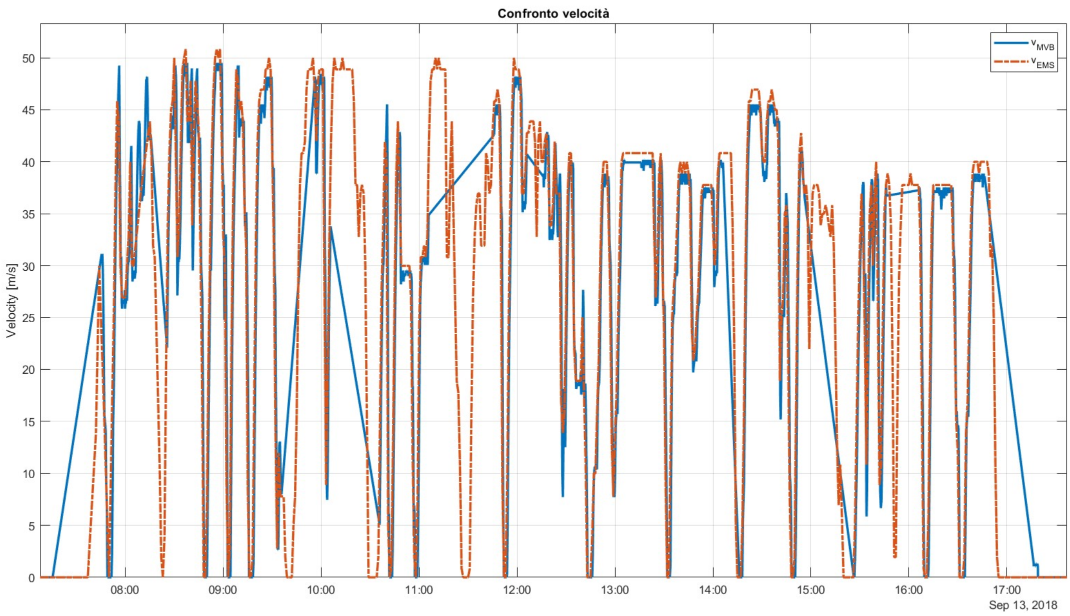

Figure 5.4 Voltage comparison

In *figures 5.1* and *5.2* is possible to observe the comparison between the GPS coordinates, latitude and longitude respectively: as already said in *paragraph 2.3.6*, the data is exactly the same, measured from MVB system and then transmitted to EMS, in order to facilitate the synchronization. As can be noted there is a complete overlapping between the two curves, apart from the instant in which the MVB lose the signal and the coordinates goes to the origin. In the graphs the curves are already synchronized, in fact, from a preliminary analysis it results that the timestamps of the two sets where shifted of two hours and three minutes, probably due to a different time zone set up of the two measuring systems. Nevertheless, after having found this time shift, it is possible to compare the variables in function of time, in order to have a univocal correspondence.

The next comparison regards the line voltage and is in *figure 5.3*: it can be noted that the curve relative to EMS voltage is always over the one of MVB, when data are present, in fact there are periods, like around 12.00, where the measure is absent. In this graph it is easy to observe the different sampling time of the two systems, in fact the MVB voltage is less constant than the EMS, whose value is a mean over the period of acquisition.

Finally, there is the velocity comparison, in *figure 5.4*: for this graph it has been used the data of another day, because the acquisition of speed by the EMS is not perfect and there are days in which it failed and so there are no available data, as happens for 15th September (the date of the other comparison). Even the MVB has some problems, but similar to the ones that has with the other variables, so limited in some time periods, easy to identify because in the graph it is a quite long straight line. However, there is a good correspondence between the two curves, although it should be noted that the MVB data has been partially manipulated, in fact the original velocity was multiplied by a scale factor which is necessary to remove for a right comparison. Some small mismatches can be observed in correspondence of periods with a constant velocity, but they are very small, less than 1m/s, furthermore, they can be addressed to a not perfect scale factor estimation.

5.2 Model validation

The validation process has been separately carried on the different components before testing the entire model and in different configurations. For this reason, there will be presented the results of the partial simulations of the main parts of the model before the complete results.

The data used as input and for the comparison with simulations results are the ones measured by the EMS systems present on the train; for the substation disposition, since there were no data, it has been considered paths supported by two ESS placed at a fixed distance of 40km. Since this is a validation, only measured data of the day in exam can be used, so the part of the train model with the power coming from the line is not present since this disturb is not available, but it is only an estimation.

5.2.1 Train position validation

The first part validated was the model area that manages the train position, because the data that it produced are necessary for all the other parts of the model. Before all, the PI controller has been tuned in order to bring stability and to do so the Matlab PID tuner app has been used. For the tuning and then the simulation, a constant value for the mass was used, because the toolbox needs a fixed transfer function to properly tune the controllers. The mass value used was $m = 550000kg$, which can correspond to a train with two locomotives, eight coaches and 500 passengers, a classic configuration for a suburban train.

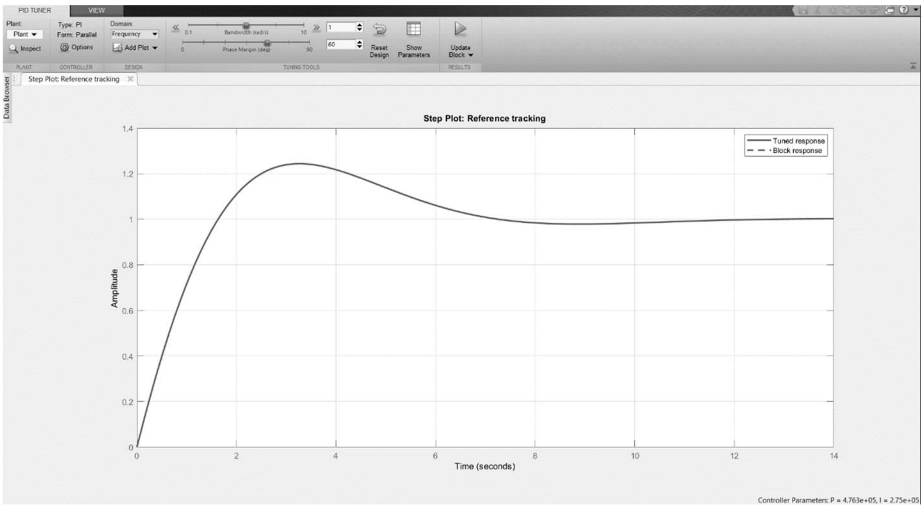

Figure 5.5 PID tuner app

The aim of tuning is not to find the fastest controller, but to realize a PID whose response could be similar to the one of a human operator, who has some reaction time and some limitations due to the vehicle specific and to his or her nature.

The bandwidth was chosen to be about at $\omega_c = 1 rad/s$, for a response time of $2s$, not extremely fast, but sufficiently for the aim of a train, and reasonable for a human person, while the phase margin $\varphi_m = 60°$, so that the system is robust enough to guarantee stability also for different train masses. In fact, if the mass has a significant change, for example $m = 300000kg$, the result is a $\omega_c = 1.259 rad/s$ and $\varphi_m = 65°$, so the stability still holds, from a theoretical point of view. In *figure 5.6* it is possible to see that the stability holds even in simulation, and the results are optimal in both mass conditions, in fact the overlapping between the three curves is almost complete.

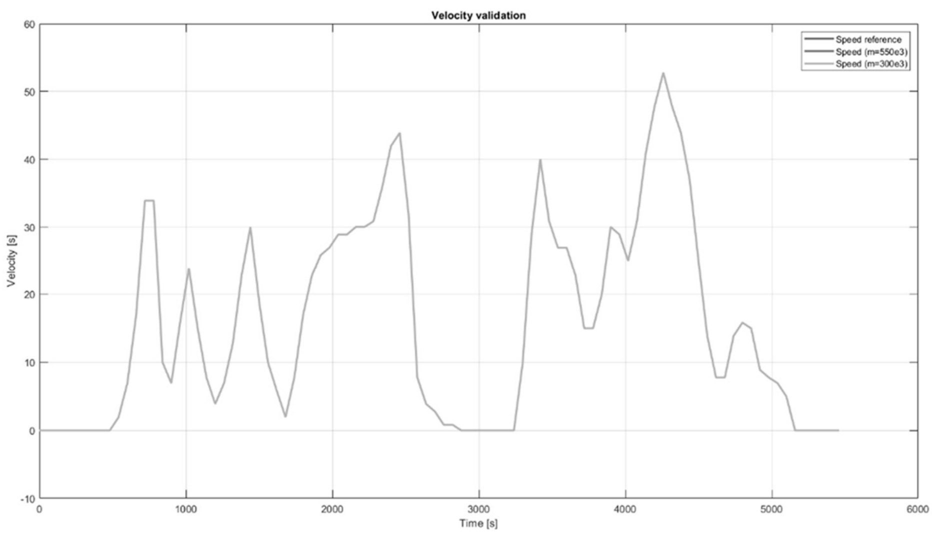

Figure 5.6 Velocity profile

5.2.2 Power validation

The next part that has been validate is the one which calculates the power demand of the train. To this aim, a new Simulink model has been created in a reduced form that only contains the train power calculation and train position model areas. Since the mass of the train is not available so unknown, it has been used a constant parameter, whose value was decided looking at the simulation results, and was fixed to $m = 250000kg$.

The train instantaneous power was not avaiable too directly, however it can be simply obtained as the product of the train current and the line voltage.

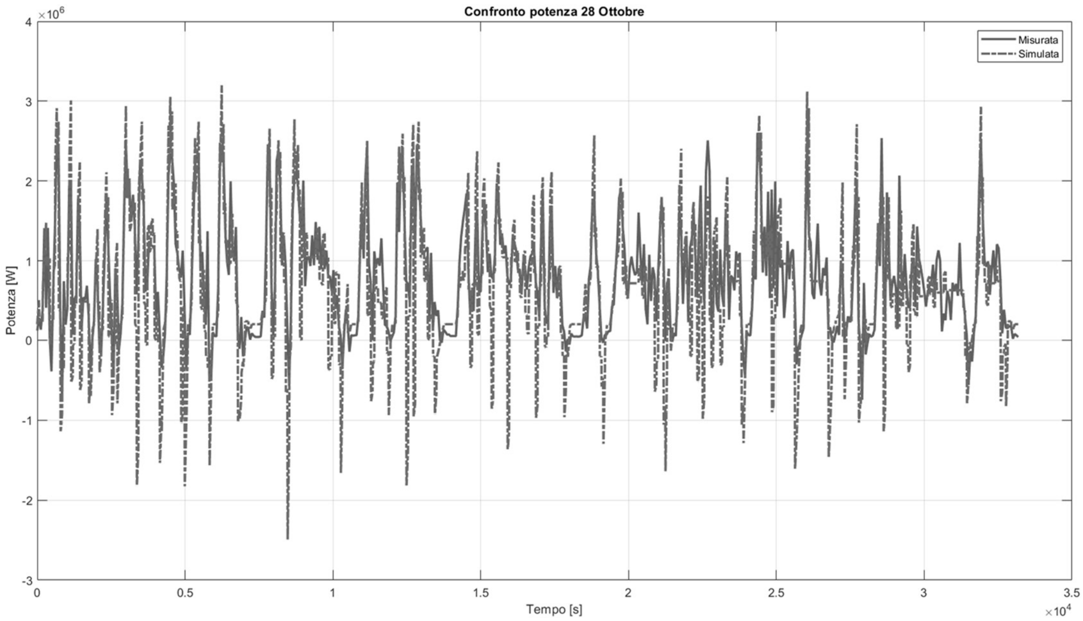

Figure 5.7 Power validation on Milan – Lecce railway

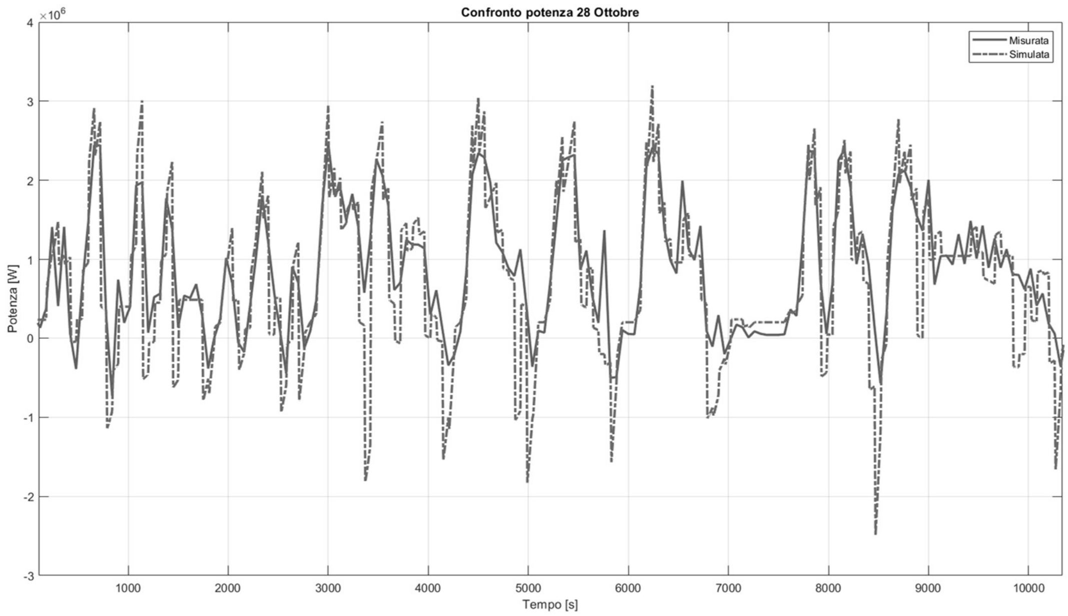

Figure 5.8 Power validation on Milan – Lecce railway, particular

In *figure 5.7* it is possible to see a power comparison on a long path (Milan – Lecce): the two lines are not overlapped, as can be easily seen, however there is a good alignment, in some cases the peaks of absorption correspond very well, like in the first period, visible in *figure 5.8*, while in other ones there is a certain distance between the two lines, nevertheless the sign (and so absorption or generation) is respected in the majority of the cases. Furthermore, there is a small error not only in transients, but also when the required power is not so high, and this confirms that the friction power is well estimated.

The greater misalignments are in correspondence of regenerative peaks, in fact the ones from simulation have a bigger magnitude with respect to the real ones, moreover in some cases, when the train is not moving the simulated power is almost zero, while the real one is positive. These differences can be addressed to a lack of information about the presence of other trains on the same path that can affect the line voltage, and to higher auxiliary consumptions.

A similar situation ca be seen on a shorter path, Venice-Brescia, *figure 5.9*: in this case the alignment is even better, the main difference remain in regenerative peaks, while for the moments with zero velocity the power comparison is consistent, so another possible source of error in comparison could be a not perfect speed estimation or measure by EMS system, because the velocity profile is the only input, with the slope one, of this reduced model, and if it is partially wrong it can bring to small error in power evaluation.

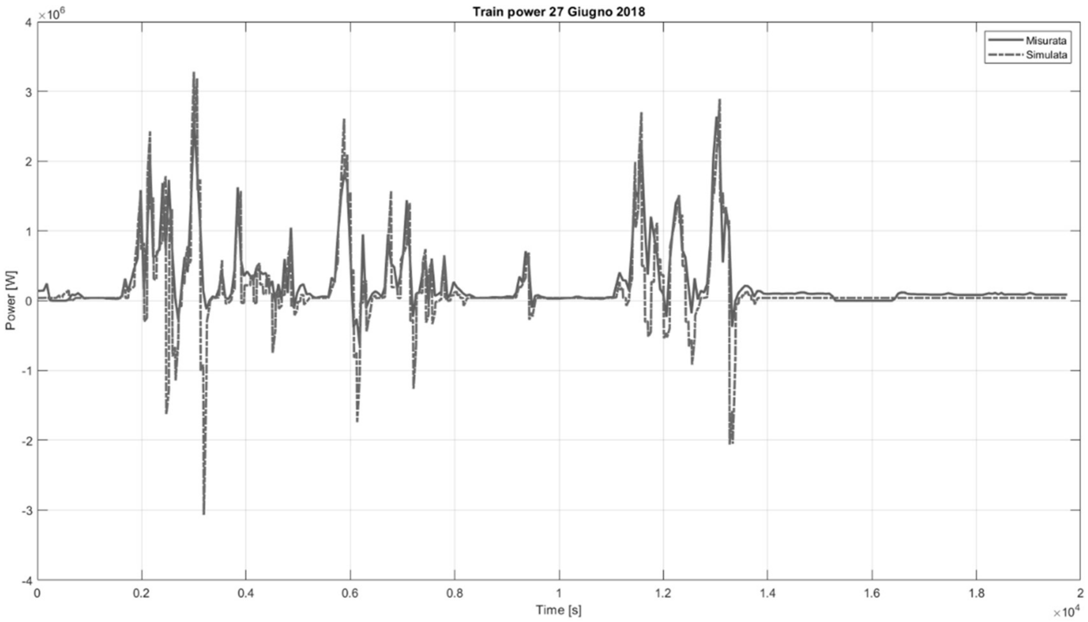

Figure 5.9 Power comparison on Venice-Brescia railway

It can be concluded that the power estimation is quite good, and it can be used in the complete model for the current estimate.

5.2.3 Voltage validation

Even in this case a reduced model has been used, consisting in train position estimation and in the equivalent electric circuit. It has in input also the measured current, that is directly the current delivered or absorbed by the train, so that the line voltage validation is not affected by possible errors in power estimation.

For the mass it has been used also here a constant value, the nominal one used to tune the controller, however here it was not important to have it the closer possible to the real one, because it affected only the mechanical transfer function and it has been seen that, even a significant change, does not cause problems in velocity control. Another important missing datum is the ESS voltage that has been supposed to be 3600V, looking at the mean value of the measured one.

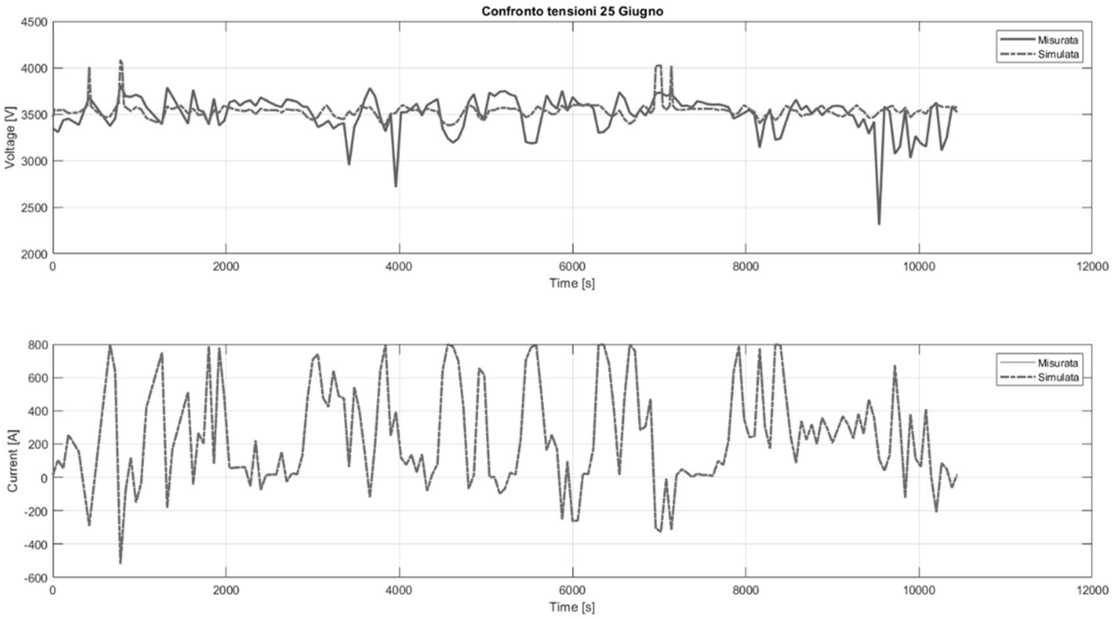

Figure 5.10 Voltage comparison on Ancona-Milan-Lecce railway

In *figure 5.10* it is possible to see the results of the simulation (of course the measured and simulated currents are the same, since it is an input and not an estimate): even in this case there is a good alignment, but not a perfect overlapping. The shape of the two curves is similar and in general the peaks corresponds, even though they can have a different value (in some cases, they are simply shifted).

The main differences are in correspondence of significant negative peaks of current, which cause voltage saturation in simulation, due to breaking rheostats, but that are significantly lower in the real case, moreover, sometimes there are voltage drops in measured voltage, absent in simulation (it is very evident around 10000s in *figure 5.10*).

The main cause of these misalignments is the lack of information about other trains on the same path: the constant power absorption in train component mimic this phenomenon, and improve the results, but the problem still holds, in fact if a train is consuming a high power, the result will be a significant voltage drop on the line, besides it can use the current regenerated from the train under examination and so the rheostats activation limit are not reached. Similarly, if it is the second train that is generating current, the result will be a voltage peak absent in simulation. Other factors are the ESS voltage and disposition, because, when the rail pass near them, it assumes the same voltage (because in the model it is something in parallel of a voltage generator, since the resistance is zero).

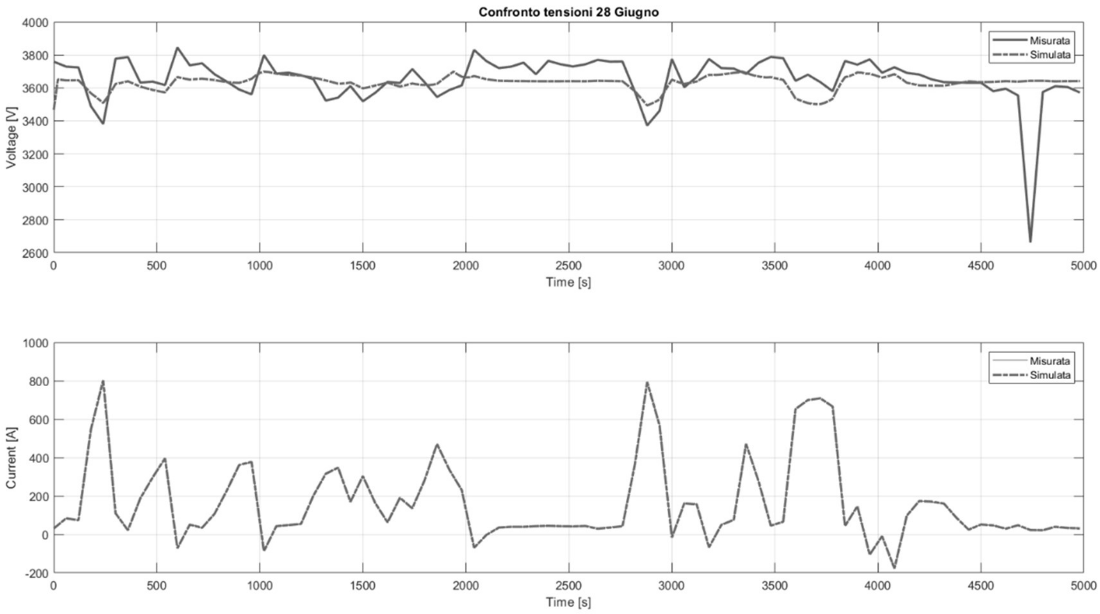

Figure 5.11 Voltage comparison on Brescia-Milan railway

Even in *figure 5.11* it is possible to see a similar case and the part of the model can be considered validate, considering the unknown information.

5.2.4 Entire model validation

After having validate the single parts of the model the next step is to check the entire one, so the only two inputs are velocity and slope profile, while the outputs are the current and the voltage, which will be compared to the measured ones to assure the correctness of the simulation results.

It will be presented the simulation for the already seen path Ancona-Milan-Lecce, with the same hypothesis for the unknown parameters.

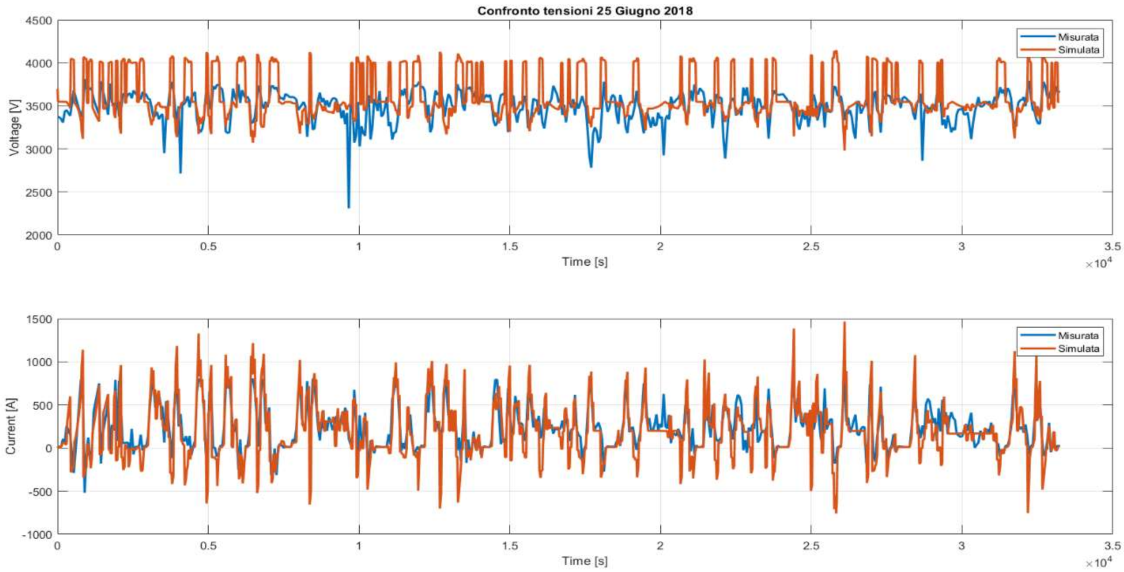

Figure 5.12 Current and voltage comparison on Ancona-Milan-Lecce railway

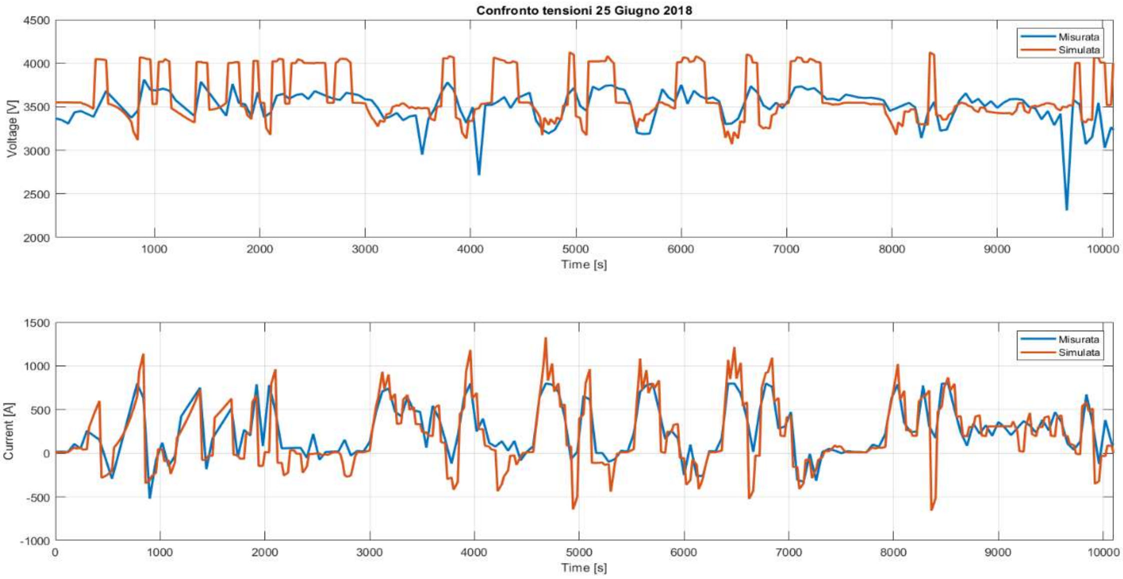

Figure 5.13 Current and voltage comparison on Ancona-Milan-Lecce railway (particular)

In *figure 5.12* and *5.13* it is possible to see the results; starting from the current it is possible to see a good alignment, particularly at the beginning; the more significant misalignments are in correspondence of peaks, in fact in the simulation they have a greater amplitude, in both direction. However, a part form this, the two curves are well aligned, due to a good power estimation but also thanks to the values that assume the pantograph voltage during the simulation.

For what concerns voltage, there is a good comparison too, in some cases the alignment is appropriate also in peaks and anti-peaks, while the main differences correspond to voltage drops in measured one and rheostats peaks: besides in many cases they are close one to another and this confirm the hypothesis on their cause, in fact if there is a train near the one under exam, it is reasonable that, after a drop there will not be a saturation peak.

In conclusion, the results of the model can be considered quite good, although not perfect and with possible improvements, even in absence of some critical data. Some parts cannot be verified because of the lack of information, such as the electrical variable of the ESS, anyway, they are linked to the other parts of the model, so they can be considered quite accurate. For this reason, a simulation with this model can give a quite realistic idea about the real variable that are at stake.

6 Simulations

After having tested the model and verified that the results obtained by it are reliable, it is possible to use it to simulate completely new situations and cases, in order to consider if a given solution could bring significant improvements in a railway network, or if it is quite useless or worse if it brings a performance reduction.

In all the simulations it has been decided to add, inside the train model, an absorbed power that is not constant as for the validation, but varying, in particular it is a real train power profile obtained on the same line but headed in the opposite direction; in this way the variability is increased and there are significant voltage drops as in measured data. Of course, the simulation with the same velocity profile will be slightly different from the real case, because the disturbance profile is not the real one, which is unknown, but more realistic in a general case, moreover the power can also be negative, when the line is not absorbing but regenerating energy.

6.1 Electric substation with battery packs

The first case study is about including accumulators inside ESS, in order to improve the energy efficiency and to see the consequent results on voltage profile. They have been placed in ESS and not on board for opportunity reasons, in fact, as already said, installing a battery on a train bring some problems such as a mass increase, a technology adjustment and also a change in the internal structure of the vehicle if it is not built with them.

The model has been simulated three times, the first one without any battery, to have the voltage profile in the case that is the common situation nowadays and that will be the meter of comparison; the second one with substation partially equipped with battery and partially not, in particular they are placed alternately, one equipped and one not and so on; finally, in the third case all the ESS contains an accumulator.

The focus of these simulations were the improvements that a generical accumulator will bring in a railway network and not which is the best technology for it, if a super-capacitor or a battery, for this reason the battery block used is quite simple, the one described in the reversible ESS with accumulator.

About the unknown data, the mass used was $M = 550000kg$, the ESS voltage $V_s = 3600V$, while the distance between two subsequent substations is always $l = 40km$. For what concerns the battery, the charging threshold was set to $3700V$, while discharging one to $3580V$, this because it is much more difficult to have $V_{ESS} < V_s$, this happens only when the maximum power of the ESS is reached and it is not so common; the battery capacity is $C = 500kWh$, taking the value from [14].

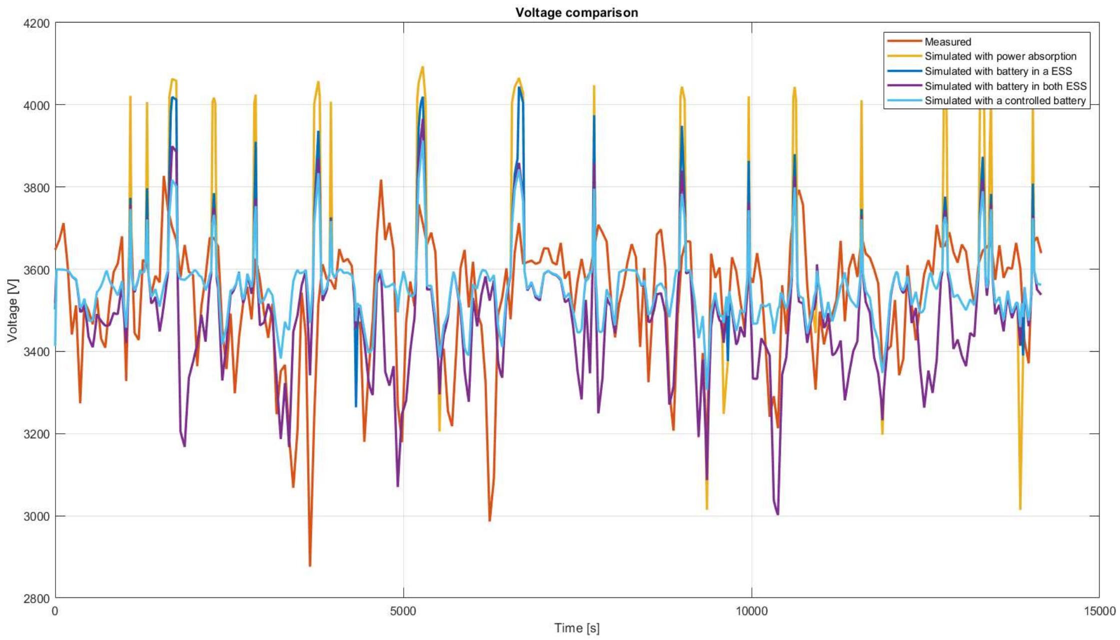

Figure 6.1 Pantograph voltage comparison

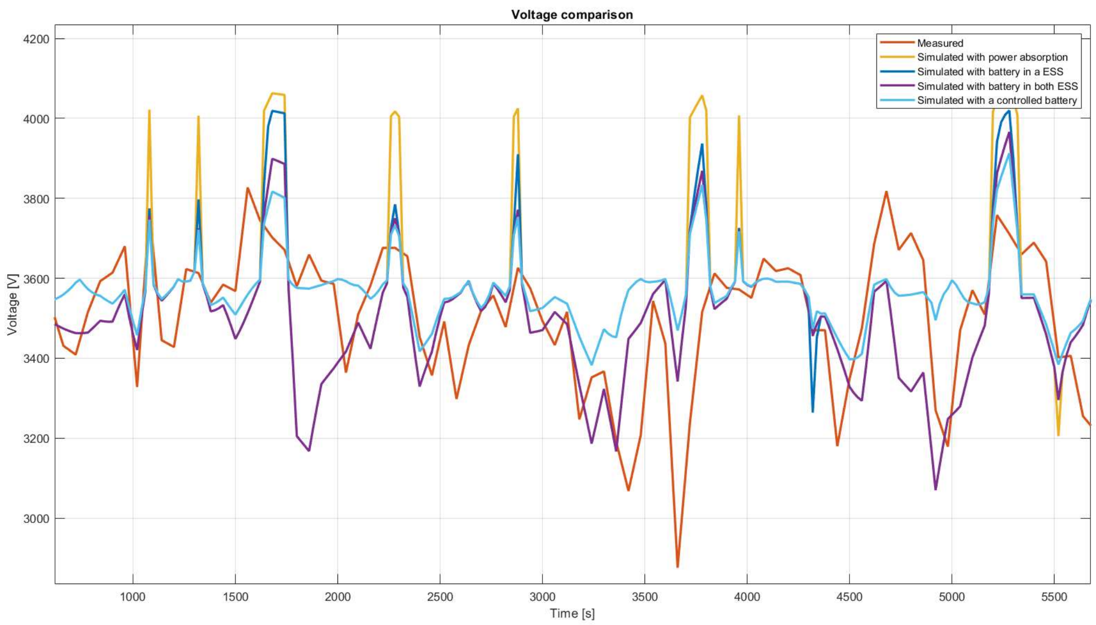

Figure 6.2 Pantograph voltage comparison, particular

In *figure 6.1* and *6.2* it is possible to see the results, it has also been plotted the measured voltage, even if it is not so significant.

It is possible to note as the presence of a battery significantly reduces the peaks of voltage so that the breaking rheostats are hardly ever used, and this fact is enhanced when the batteries equip the ESS on both sides, while for drops the improvement is significative only in case of very large ones (the most visible case is about at $t = 14000s$), when the substation cannot provide all the needed power.

The result of this application is an overall reduction of the voltage variance, moderating the peaks, however the effect is not still so good, because voltage drops still have a great amplitude and it would be nice reduce it, even in case of powers deliverable from the ESSs. A possible solution, is to link the battery current supply to the pantograph voltage, for a sort of hysteresis control, to this aim a new version of battery pack component has been declared, starting from the previous one: the main difference is that this one has also an input, which is the train voltage. Since this is a quantity already measured and transmitted in real time to the Spanish server via GPSR by the experimental trains that provide data, it could be also possible to send it to the nearest electrical substation which implement this control, so with marginal changes in the infrastructure, in fact it would be only necessary to install the measuring and transmission system on each interested train and an analogous receiving system in the ESS equipped with controlled batteries. In this way, this strategy does not need a huge use of resources to be employed but bring significative improvements not only from an energetic point of view, with an overall efficiency increase, but also for line voltage profile.

About the component functioning, it changes only in the dead zone, in fact, if it is in it, the input is considered and compared with two other thresholds V_3 and V_4 to decide if injecting or absorbing current. A good choice is $V_2 < V_4 < V_3 < V_1$ possibly with a certain difference between the ESS and the train thresholds, to guarantee currents sufficiently large to have appreciable results. Moreover, the interval between V_2 and V_1 should be bigger than the one in the case with the normal battery, otherwise the input could be hardly ever considered. For all these considerations, it has been chosen to set the parameters as shown in the mask in *figure 6.3*, furthermore, the distance between two subsequent substations has been reduced to $l = 20km$, a value which is closer to reality and that reduce the catenary resistance level. About the disposition of these controlled ESSs, they are located alternately to a ESS equipped with a simple battery.

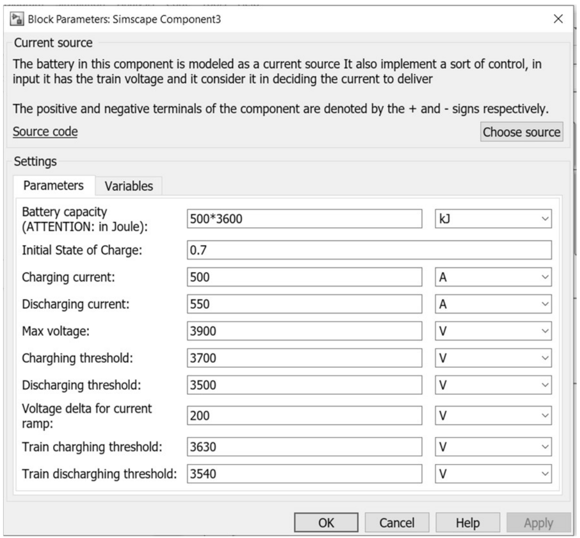

Figure 6.3 Controlled battery mask

The result is the light blue line in the comparison figures: as can be easily seen, now the voltage is much closer to the reference one $V = 3600V$, but above all, it presents variations significantly reduced in their amplitude, not only the peaks, but also the drops, besides the battery present a greater utilization, in fact while in the case without this sort of control it was essentially charged, because it was difficult to go under V_S in the substation, in this other case the accumulators are mostly used to support the line, so it could be necessary to partially charge them when there are no utilizers in the tract which they support to avoid to reach $SoC = 0\%$, however the battery capacity is big enough to guarantee a certain autonomy.

It could also be possible to use controlled ESSs on both sides, however in this simulation this was not tested for a control reason: in general it is common to have that a substation support more than a single train, and these vehicles will be in different position along the railway and so with different pantograph voltages; it is impossible for a single battery to control more than one train, so, even in case of controlled accumulators on both sides, the train voltage is sent as input to only one at most (because there can be more trains than controllers). However, having a control reduce the entity of disturbances between trains, because guarantees a flatter line voltage, so brings advantages even to not controlled utilizers.

6.2 Simulation with different velocity profile

The main component of the total power request of a train is the traction power, because, although the accelerations are not very high, the vehicle mass is significative; therefore, a reduction of traction power would bring to interesting energy savings. Observing a typical velocity profile, it is possible to note the presence of many velocity variations which are not required, for example a brake and a successive acceleration without the presence of a stop. A reduction of these changes and the consecutive adoption of more regular profiles could bring some benefits to railway system, so it may be interesting to investigate them.

As a natural consequence, another case study evaluates the effects on power request when the velocity profile varies, in particular there have been considered trapezoidal velocity profiles (TVP) with different values of accelerations from $a = 1m/s^2$ up to the minimum accepted value, which modify the profile in a triangular one, and they have been compared to the pilot's one. In addition, even a trajectory evaluated with a third order polynomial (TOP) has been considered, to evaluate a possible different approach, even though it is not easily applicable to trains.

The model simulated the medium distance rail route Venice – Brescia, considering as intermediate stops the ones that one of the trains that provides data made on 27th June 2018, in this way a comparison was possible.

For the generation of the new trajectories, it has been considered that the train cannot reach the destination before the arriving time and has as additional constraint only the maximum desired acceleration. For what concerns the velocities, they were checked a posteriori to control that they were not too high, but were all acceptable, in fact the maximum one was $v = 45m/s = 162km/h$ acceptable for this kind of locomotive (whose maximum speed is above $200km/h$) and for the path, in fact the peak velocity of the pilot ($43.3m/s \cong 156km/h$) has been reached in that sector. In a similar way, it has been checked that in all cases the covered space was effectively the length of the route.

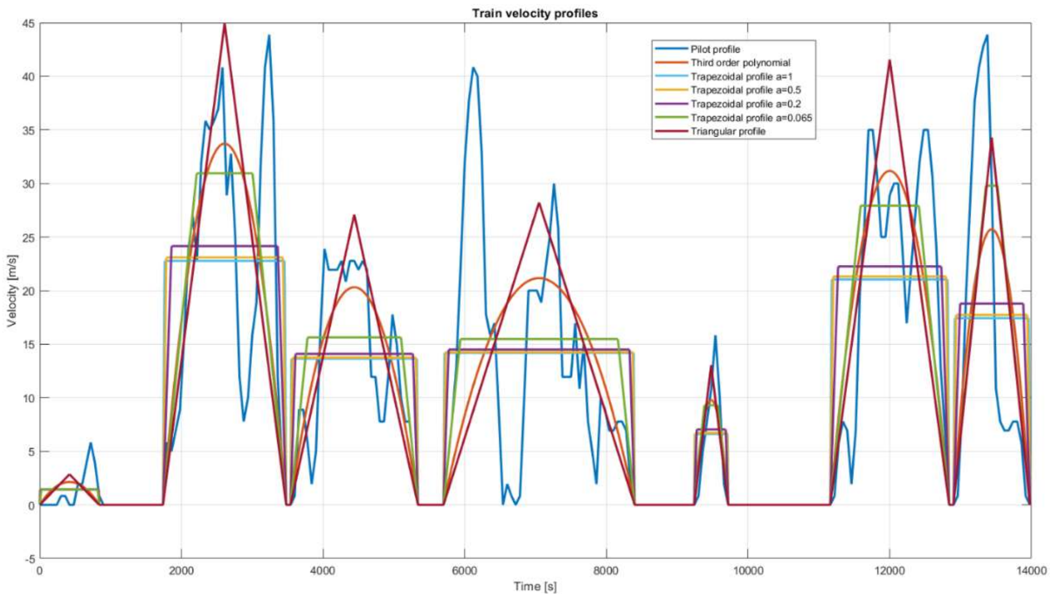

Figure 6.4 Train velocity profiles along Venice - Brescia route

Looking at *figure 6.4*, it can be noted that the calculated profiles are significantly more regular with respect to the pilot's one, which includes many more accelerations and braking, moreover in some cases there are also some arrests and successive restarts. For what concerns accelerations, they are usually smoother than the ones of the first two trapezoidal cases, the maximum $a = 1m/s^2$ and the half of it, but higher than the three other cases. A velocity comparison is not easy to do, because the pilot's profile irregularity, however his speed is generally higher than the evaluated ones, only the triangular case is greater in a pair of sector, the second and the sixth, while the trapezoidal with the minimal common acceleration that guarantees the feasibility of the covered space is always below the peaks and with a maximum value of $v = 31m/s \cong 112km/h$, and the others travel much slower. Besides it can be noted that the two profiles with $a = 1$ and $0.5m/s^2$ are very similar in this route: a halving of acceleration does not bring significative changes in cruise velocity: for this reason, and also looking at corresponding power consumption, in this case it is better to avoid the profile with the maximum acceleration, which does not bring significative improvements for the velocity, but has power peaks of double amplitude that can bring problems for energy feeding, so this profile was not considered in simulation. Similarly, even between triangular and third order polynomial profiles a choice was made, because from velocity point of view they were not very different in shape; the excluded one was the first because it reaches higher velocities, with the risk of overcoming limits, and requires higher powers.

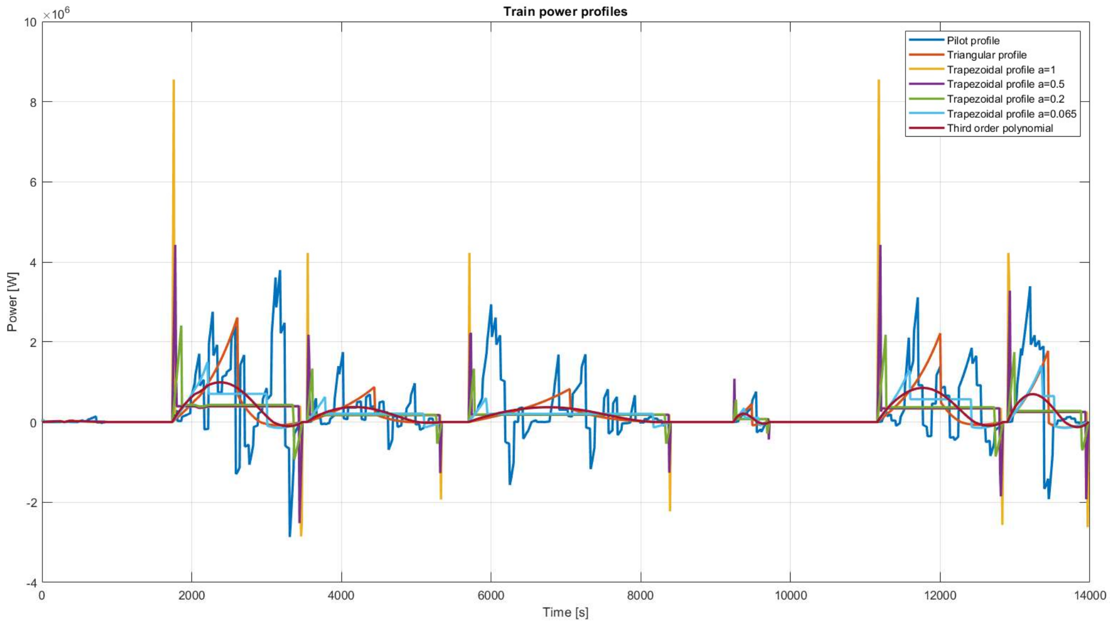

Figure 6.5 Train power profiles along Venice - Brescia route

In *figure 6.5* it is possible to see the different power profiles, considering a train mass $M = 300000kg$. The power simulation was carried on before the complete one to check if there were present too high peaks, as for the first trapezoidal profile, while the other are acceptable with this mass, in fact this variable is an important issue because if the vehicle has a double mass, like a full high capacitance train, even the acceleration $a = 0.5m/s^2$ required too high powers (for the simulation there were considered electrical substation with a power limit $P_{max} = 3.6MW$).

The real problem with a trapezoidal profile is that the maximum acceleration is kept until the maximum velocity is reached, so that the inertia force remains constant while the velocity and so the power increase. This is the main reason for which the third order polynomial has been considered: in a future development for optimization of velocity, it could be considered a profile with an acceleration similar to the one of a third or better fifth order polynomial that reach a cruise speed.

The third order polynomial is the profile with the lower power peaks, a bit more than 1MW, so can have application in rail with limited ESS or high traffic, moreover it could be noted that it is always positive, because the deceleration is slow and it is sustained by the aerodynamics and specific friction, especially at the beginning, while at the end the regenerated power is lower than the auxiliary consumption, so it is completely used inside the vehicle, and this brings to a lower probability of braking rheostat usage, important in a line without any active ESS, like the one in simulation, to avoid voltage peaks.

After these preliminary analysis, the complete model could be simulated with five different profiles to compare the results especially for line voltage and energy consumption.

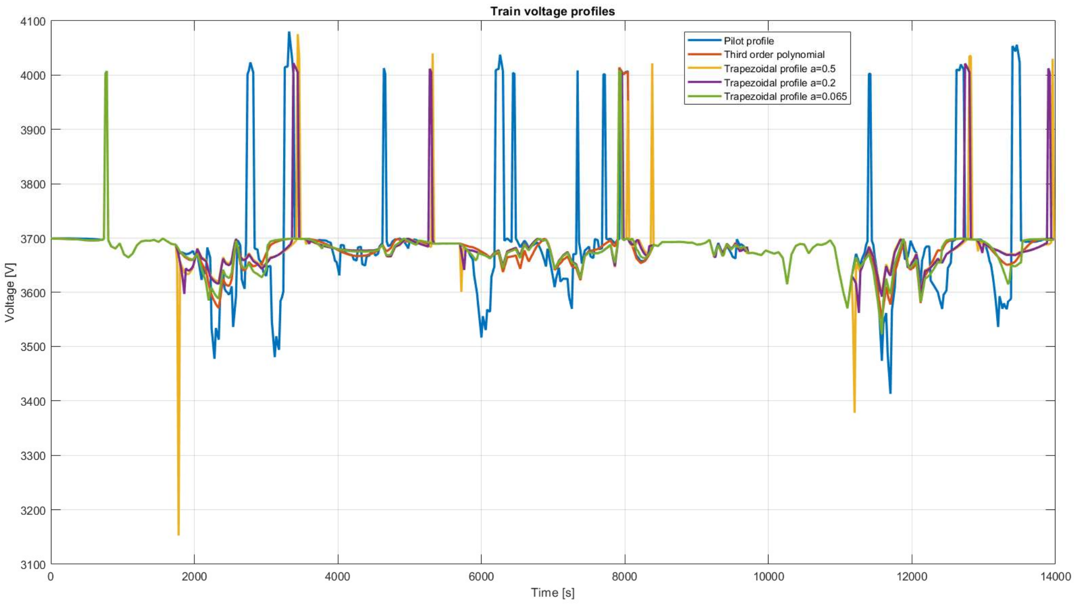

Figure 6.6 Train voltage profile along Venice - Brescia route

It is immediate to see that all the new trajectories have a more regular voltage profile, with less peaks and drops more limited in amplitude and duration, thanks to the more uniform speed. Only the trapezoidal profile with $a = 0.5m/s^2$ in two cases presents deeper drops, but for a short time, however the amplitude is still acceptable, 3150V, inside line limits. The two profiles of simulation with higher accelerations are almost overlapped for the majority of time and generally contained in the interval 3600-3700V, the main difference is the number of peaks minor when $a = 0.2m/s^2$. The voltage profile of the other trapezoidal velocity profile is a bit different, its drops are generally less relevant but last for a longer time, while in deceleration phase it is closer to the reference voltage $V = 3700V$ and presents a lower frequency of high peaks (braking rheostats are activated only twice in this simulation and the first time is due to external causes). For the remaining trajectory, it is quite similar to the last one, in the first part, it is usually closer to the reference, the contrary in the second, when the other travel with constant speed: this is consistent with the currents behaviours in *figure 6.7*, where is possible to see the periods in which one is greater than the other, besides it is possible to note that the continuity in current for the third order polynomial profile, causes less variation in voltage with respect to a step change due to catenary and filters inductances.

About currents magnitudes, during braking, the greater are the ones of the pilot and of the more aggressive profile, while for the two smoother profiles there are never negative values; for the peak ones, the pilot require quite often currents between 500 and 1000A, while the trapezoidal profiles can require greater currents (at most 1464A) but for significantly shorter periods, and in general the peaks are below 750A.

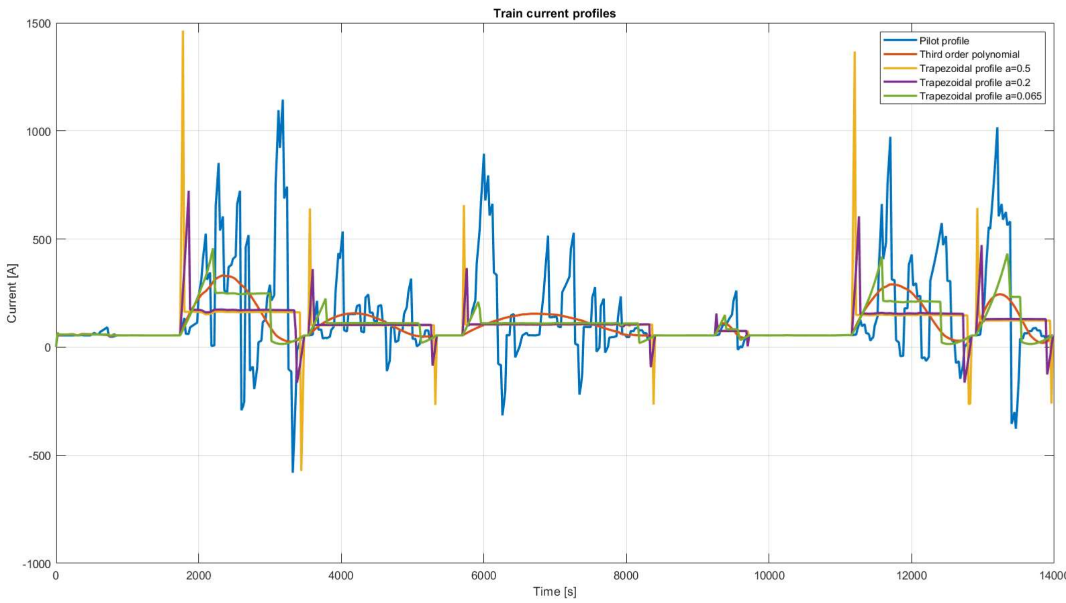

Figure 6.7 Train current profile along Venice - Brescia route

Finally, it is possible to evaluate the total energy consumption and it is evident the difference between the pilot and the evaluated profiles, about 2GJ, the 26,7%, so a very significant saving is possible acting on it.

The differences between the new profiles are less relevant, about 150MJ; it is possible to see that the less consuming is the one with $a = 0.2m/s^2$ followed by the most aggressive, then, a bit separated there are the third order polynomial and the last trapezoidal. These relative distance is due to the aerodynamical losses, in fact the first two profiles have lower cruise speed and the corresponding saving overcome the greater traction energy demand.

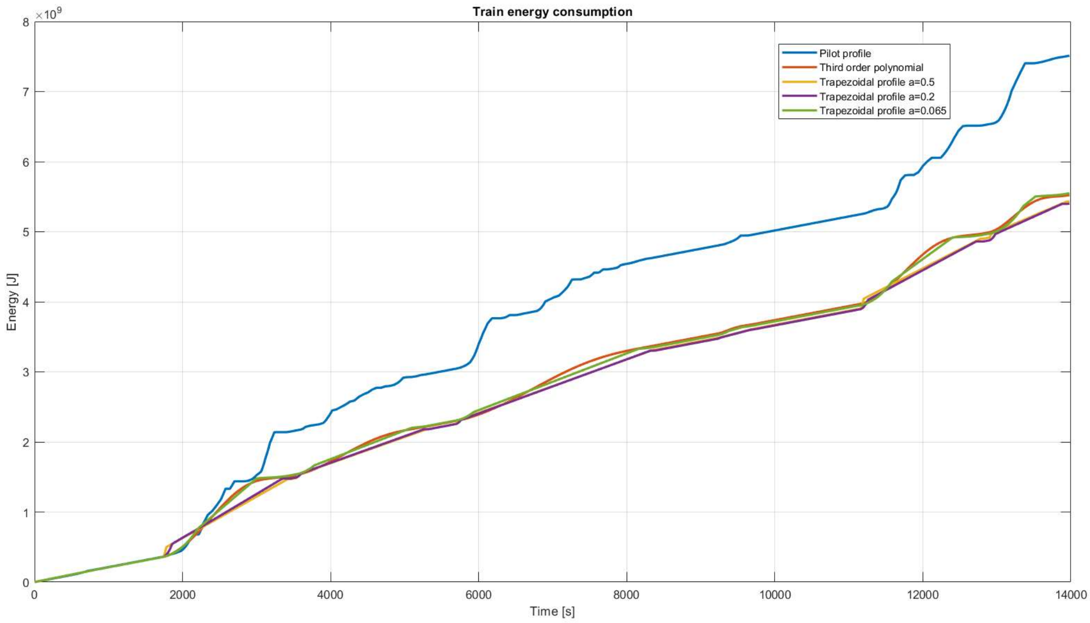

Figure 6.8 Train energy consumption profile along Venice - Brescia route

In conclusion it is not easy to declare what is the best profile, but it is easy to say that the worst is the pilot one, because the two trapezoidal with higher accelerations has a lower energy consumption but greater voltage variances and current peaks, while the other two trajectories the contrary: it depends on which is the priority. In the table below, there is a small overview.

Profile	Voltage RMS deviation (V)	Max current (A)	Max power (MW)	Max velocity (m/s)	Energy consumption (GJ)
Pilot	98.6	1145	4.0	43.9	7.51
TOP	50.4	331	1.2	33.7	5.52
TVP a=0.5	59.0	1780	4.6	23.1	5.43
TVP a=0.2	58.2	723	2.6	24.2	5.40
TVP a=0.065	43.4	457	1.6	31.0	5.55

Table 6.1 Results obtained with different velocity profiles

6.3 Simulation with different velocity profiles and with battery storage

The next step after the two previous case study is an overall analysis which consider both of them, in order to evaluate the consequences in case of a double adoption of these enhancement strategies, to see if some conflict can arise or if the performance improvements was strengthen.

The data upon which the simulation is based are the ones collected by the train, whose identified number is 777, the 30th August 2018, in the path Venice – Bologna. It has been chosen this particular set of data, because in this date the train travelled in a normal work condition for a passenger train, in fact its stops correspond to real rail stations, while, at the contrary, in some other days the stops were quite random, because the train was out of service or it has some problems. In this case, comparing the velocity profile with the GPS position, it is possible to note that the train starts its journey from Venezia Santa Lucia station, to arrive in Bologna Centrale, with the intermediate stops in Venezia-Mestre, Padua, Rovigo and Ferrara as can be seen from *figure 6.9*. Besides another choice criterion was that the travel time was long enough to have meaningful results, but not too much, to have reasonable simulation times.

Figure 6.9 Train path on 30th August 2018

After this part was checked, it was also taken a value of mass that was the closer possible to the real one: to this aim, a comparison between the measured power and the estimated one based on pilot profile was carried on, with the same procedure used in validation, and the better result was obtained with a mass $m = 250000kg$ (typical of a regional train).

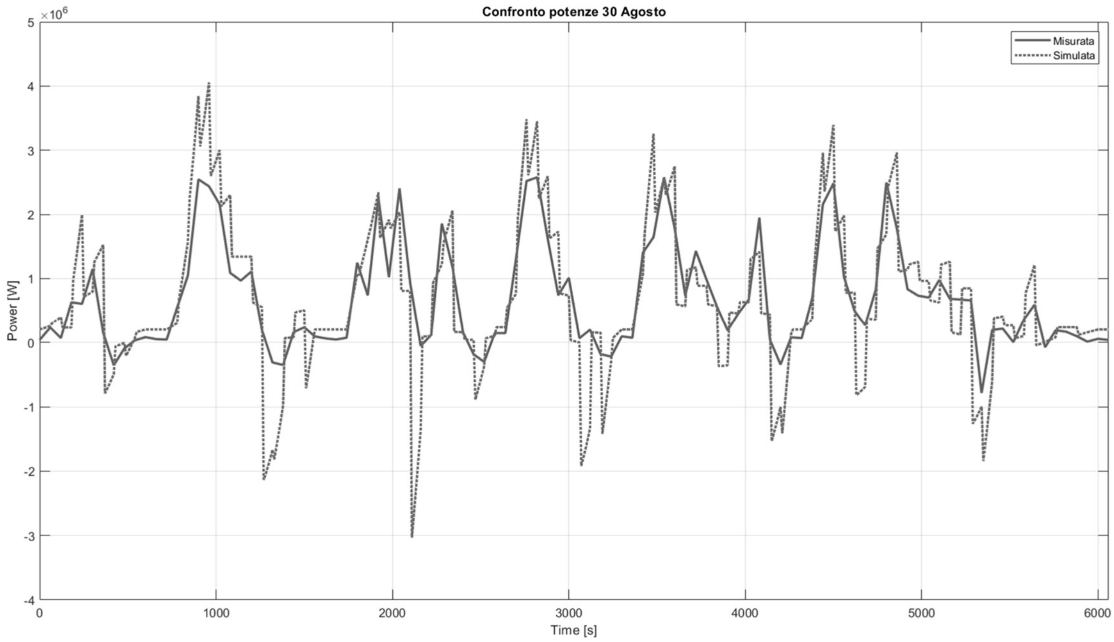

Figure 6.10 Mass validation

At this stage, the different velocity profiles could be calculated, with the same logic used in the *section 6.2*. In this case, the acceleration chosen for the trapezoidal velocity profiles were the maximum possible, $a = 1m/s^2$, two intermediate values, $a = 0.5\ and\ 0.3m/s^2$, and a minimum common value of acceleration $a = 0.16m/s^2$. Then there were the triangular and the third order polynomial velocity profiles to conclude the set.

An analysis of the velocity profiles shows that two of them are unfeasible, because they overcame the locomotive limit velocity that is $v = 200km/h = 55.56m/s$: this it is easy to note in *figure 6.11*, because in the path between Mestre and Padua the pilot touch this limit, without overcame it, of course, and, at the same time, the TVP with the minimum acceleration and consequently the triangular profile lines are above the pilot one. The other profiles are all feasible, in absence on information about limits in particular parts of the path, however, apart from the TOP in one occasion, the maximum speed reached in each single portion of the complete route are above the pilot one.

From the preliminary power analysis in *figure 6.12*, there is another exclusion, of the most aggressive TVP, because its peak is higher than 10MW, so too high. Even the

TVP with $a = 0.5m/s$ has peaks with an amplitude that is 50% more than the one of the pilot, but these are still acceptable for the electric substation limitations.

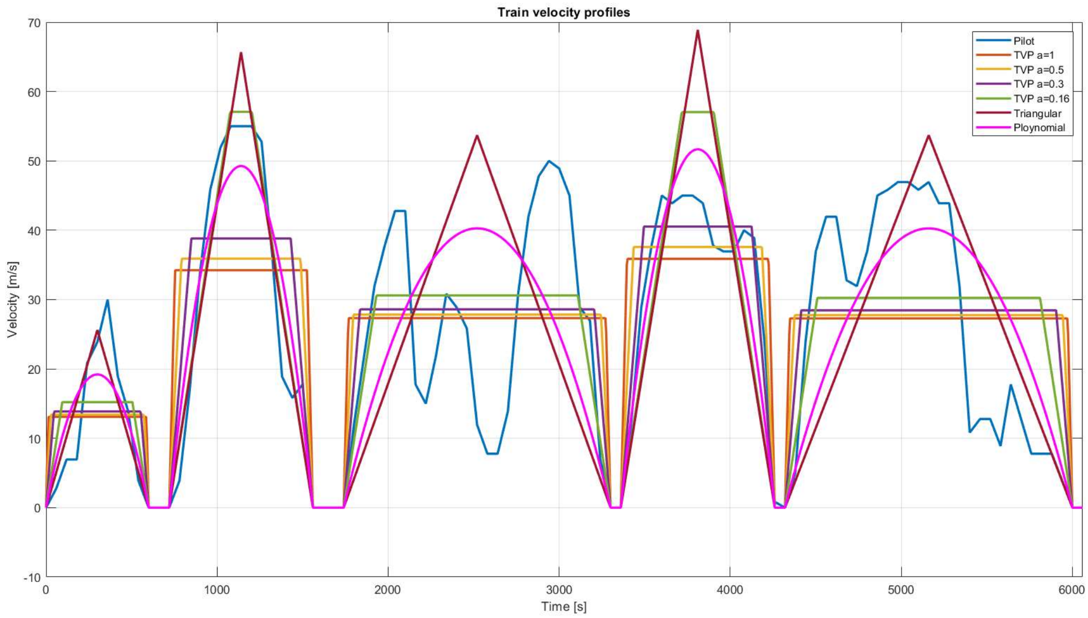

Figure 6.11 Train velocity profiles on Venice – Bologna route

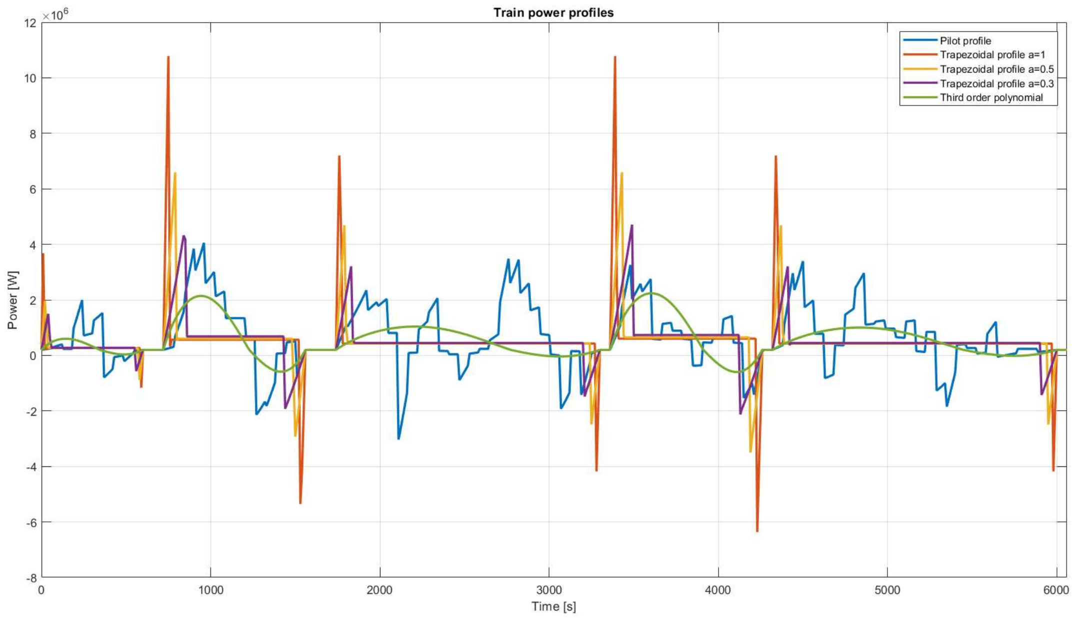

Figure 6.12 Train power profiles on Venice – Bologna route

The considerations about the selected profiles are similar to the ones already done, the two TVP have got higher power peaks, but when travel at cruise speed the request is quite limited. The TOP has lower request in amplitude, but with longer duration, moreover, in this case, even it enters in regeneration mode around 4000s.

At this point it is possible to analyse the simulation results, visible in *figure 6.13, 6.14 and 6.15*.

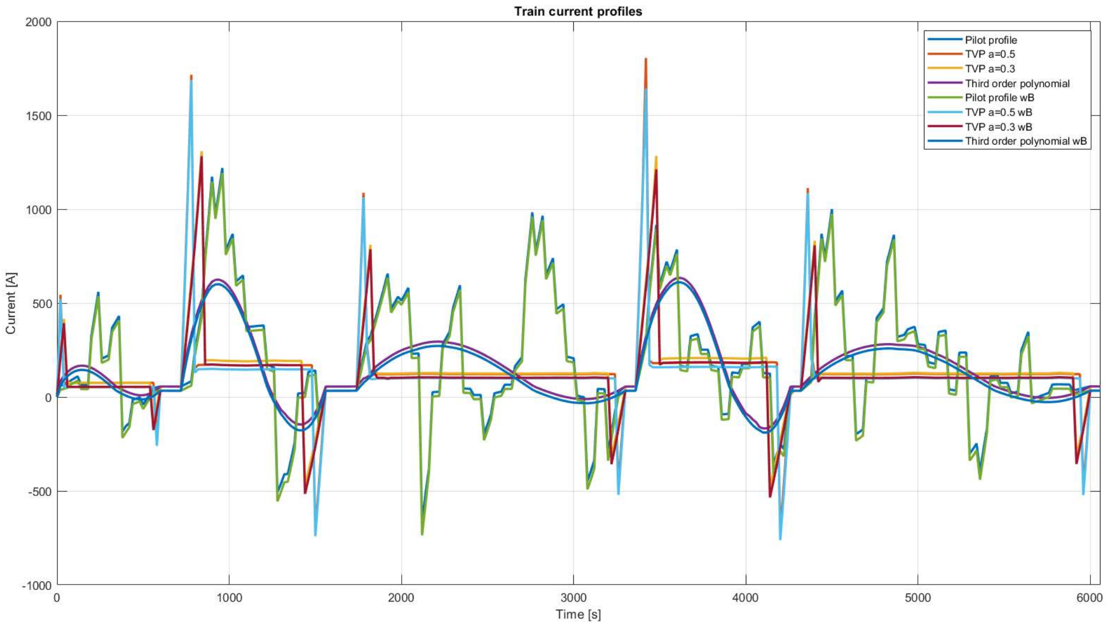

Figure 6.13 Train current profiles on Venice – Bologna route

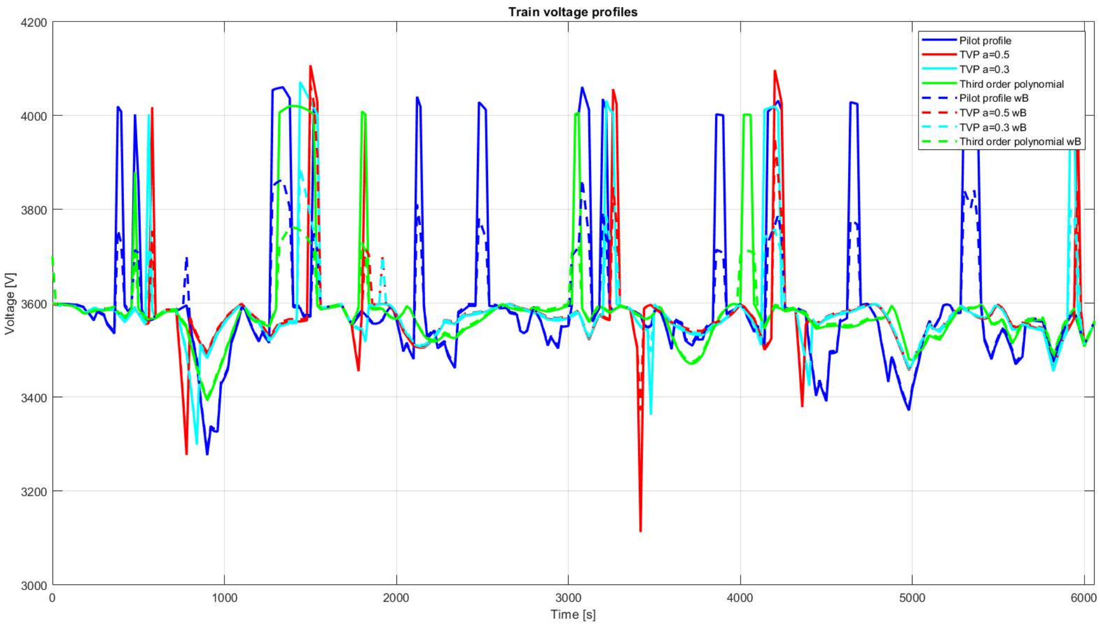

Figure 6.14 Train voltage profiles on Venice – Bologna route

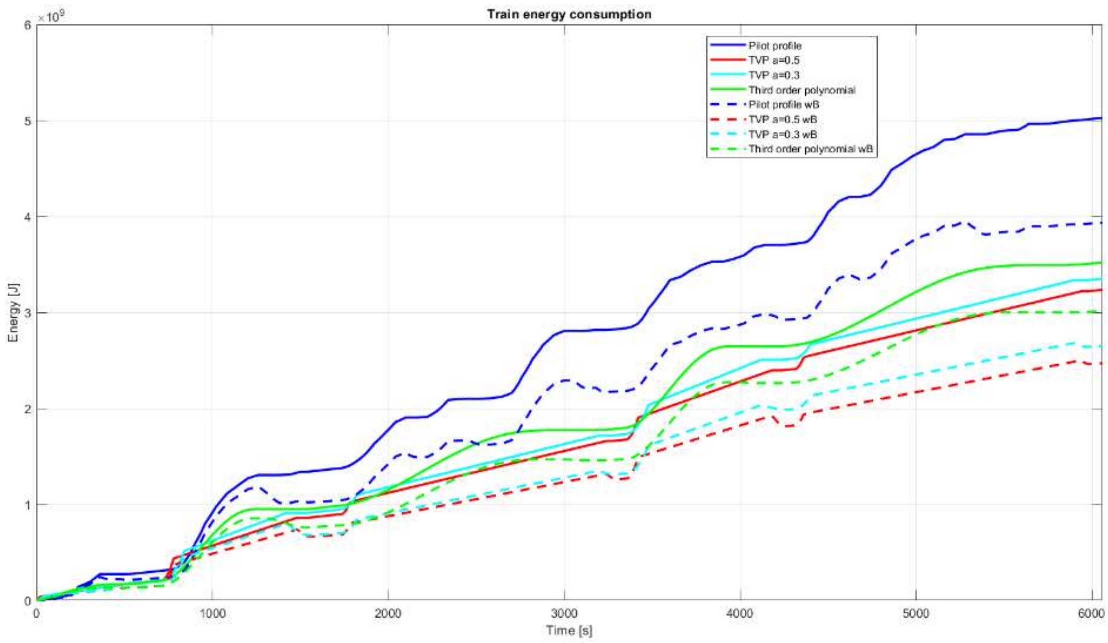

Figure 6.15 Train energy consumption on Venice – Bologna route

The simulation hypothesises are not very different from the ones already used, here the ESS voltage is $V_{ESS} = 3600V$, with distance between two subsequent ESS $l = 20km$. For what concerns the battery, in the simulation in which they are present, they are installed in both the substations.

Starting from current, the results are not very different from the power profiles, the differences are between the profiles with ("wB" in the legend) and without battery, in fact it can be noted that the first ones have positive values smaller than the second ones, while when the current is negative the behaviour is the contrary. The explanation is quite straightforward, in fact it is a direct consequence of the flatter voltage profile, since the current request is obtained as $I_t = \frac{P_t}{V_t}$, where P_t is the train power and V_t the pantograph voltage, the reduction of voltage drops in correspondence of peak of absorption brings a higher denominator value and so the result is a current reduction, which can arrive, in the most favourable case, at 160A. The phenomenon is the same even when the power is negative, with the only difference that now the voltage has peaks which are lower due to battery action and so a lower denominator bring a higher absolute value of the result.

This phenomenon can have its relevance, because the medium value of the current circulating in the railway line is reduced, because it is more common for a train the absorption with respect to the energy generation, and this bring a lower dissipation in the catenary, that is a small advantage of the usage of battery inside electrical substation which can bring to significant energy savings in a year.

Looking at voltage, it is possible to see that the presence of batteries introduces a significant improvement for each type of velocity profile: this is particularly important for the most aggressive tested profile the TVP with $a = 0.5m/s^2$, in fact here the voltage variation which are very consistent are reduced, for example the minimum value of voltage reached is 3283V instead of 3113V, moreover even the peaks are reduced in duration and, in some cases, also in amplitude: in this way the greater disadvantage of this generated trajectory, although it is not completely solved, is made more acceptable.

The root mean square (rms) of the error using batteries is always reduced, and this reduction is variable, but it is at least halved, in the case of TOP, the reduction factor is even 2.6, 3.17 with respect to the pilot's one (without batteries), so a combination of the two strategies have very good effects in making flatter the voltage profile, with the consequent benefits.

In case that only one of the two strategies could be applied, in this field it is better to act on batteries, because the reduction of the rms is greater than the one that can be obtained acting on velocity profiles, for this path the reduction only with battery is a halving, while only acting on the pilot the improvement is about 18% (while with both of them it is 69%).

For what concerns energy consumption, it is the contrary, in fact it is easy to note that acting on the velocity profile bring a greater reduction with respect to only adopting regenerating ESS (in energy profile, the regenerated energy has been subtracted from the consumed one): even in the worst case, which is the TOP, the difference between the energy consumption of the pilot with batteries and the third order polynomial without is 0.42GJ and this difference arrives till 0.7GJ with the TVP with $a = 0.5m/s^2$, moreover the adoption of a better driving style is significative less expensive and the presented solutions can be further improved through an optimization.

However even in this field, the benefits in applying both strategies increase, in fact looking at the pilot and the TVP $a = 0.5m/s^2$, which is the best for what concerns consumption, the reduction is 36% and can arrive to 51%, which corresponds to 2.53GJ saved, with the further adoption of batteries.

Of course, the reduction due to accumulators is greater with the pilot's profile (1.08GJ while for the more aggressive TVP is 0.73GJ), but, looking at the percentage, the difference becomes only some point percent, actually, for the mentioned profile, it is even better, however it is usually around 22%, apart from the TOP for which it is only 15% because of its power profile that regenerates less energy.

In conclusion, the adoption of these two combined strategies can bring to very significant improvements for each variable of interest, in particular the consumption can be halved with a simultaneous enhancement in voltage profile and in current transmission losses, moreover the disadvantage that the change of velocity profile brings for high acceleration, that is the voltage drop during acceleration, can be mitigated by the adoption of the other technology overcoming the doubt that can prevent from applying it.

7 Conclusions and future development

This thesis started analysing the actual technologies used in Italian railways, focusing particularly on DC traction, which represents the majority of the lines and because the available data were about two passenger *Frecciabianca* trains.

The information collected with this analysis have been used to prepare a Simulink Simscape model, which guarantees affordable results that could help in other studies, with a special focus on its reusability, in order to have the possibility to use it even in situations different from the ones for which it has been created and validate, without the necessity of great variations and further validations.

Then it has been presented some technologies that are being studied and in some cases that has been also applied, experimentally and even in a permanent way, to reduce the total railway energy consumptions and consequently the carbon footprint, in order to have better possibilities to reach the savings targets discussed in the introduction. These recovery strategies are all based on the recycling of the braking energy generated from trains motors and now generally wasted: there are some different possibilities whose adoption depends from the situation of the existing railway infrastructure and planimetry, trains and other factors, one of which, not negligible, is the economic one.

From some of these solutions, a Simulink component have been obtained in order to be add to the existing model, to have the possibility to test its impact on a railway in simulation before or in substitution of a test with the physical component, which is much more expensive.

7.1 Outcomes

The model has been validated firstly in its main parts and then in its completeness, to check that the results were consistent to the measured ones and so reliable. For this process it has been used the measured data obtained by the EMS system regarding some paths of different length, from regional to national routes of almost 1000km. In particular, the data of main interest were the train velocity, the current and voltage, from which it has been obtained the power, and the GPS position necessary to extract data regarding the declivity and tortuosity of the path, which determine the accidental resistances.

Then these data were partially given as input to the model, depending on what validation was being carrying on, and partially used for a comparison with the outcomes of the simulation. The results are quite satisfactory, in fact, although there is not a complete overlapping between the two curves in any case, the differences are never crucial or critical, the trends are respected and the alignment, as can be seen in the graphs shown in *section 5.2*, is all in all good.

The most relevant mismatches are mainly due to lacks of information, for example, it has been noted that the line voltage is largely affected by trains consumptions and regenerations of energy and, since in a section of railway it is quite common to have more than one vehicles at the same time, it is impossible to predict the exact pantograph voltage of a train knowing all its data, but ignoring the power coming from other utilizers. This problem has been partially solved inserting another utilizer in the line in correspondence of the train with a reasonable power profile. Other information is more easily implementable and could be effortlessly found such as the train mass and the electric substations disposition and their nominal voltage on a specific line.

The validated model has been used to test some configuration that may bring to energy savings as done in *chapter 6*. Here there have been tested two different strategies, then combined each other to see if the results were strengthened or not. In *section 6.1*, it has been examined the adoption of one of the recovery strategy exposed in *chapter 4*, the ESS equipped with accumulators: some simulations have been done to check the results from a partial and total adoption of this technology and of an enhanced one which also includes a basic control on the train. The outcomes have been compared to examine if there were improvements for pantograph voltage profile, because if it is more stable and constant, also the current receives some benefits; it has been observed some improvements in reducing peaks and drops that reduce the root mean square of voltage deviation.

Then, in *section 6.2*, it has been studied another power reduction strategy, which is easier to implement, from a certain point of view: a change in velocity profile. The simulation with pilot profile has been compared to simulations with more regular profiles, because one of the causes of consumption are the irregularities in vehicle motion. From an economic point of view, it is more simply implementable, because it does not required actions on the existing convoys and infrastructures, as the adoption of batteries, however it requires that the pilots strictly follow the given profile, without significant deviations, so there is the problem related to human factor, which could be removed with an autopilot like the one used in undergrounds, but this would bring additional costs. Nevertheless, it has been noted that this solution, from the energetic point of view, is better, because it entails a superior reduction of consumed energy, with respect to the previous one, so it could be further investigated for the future.

As briefly shown, the potential of this model is significative, because it is reliable enough to be used to test new configurations and new solutions with money but also time savings; in fact, it is not extremely rapid as could be a block-oriented model, because its object-oriented nature implies the presence of more variables, which makes it also more precise. However, the computational time is never higher than the simulation time, and this allows to have an object-oriented model which can simulate even long paths.

7.2 Future works

The work of this thesis could be expanded thanks to the versatility of Simscape, in fact with this instrument it is much more easier to add particulars; for example, it could be possible to substitute the voltage source in electric substation component with a Graetz bridge rectifier or with a thyristor rectifier, depending on what is the aim, to study also the electrical dynamics, not in a limited time interval as already done in the past, but on an entire path, keeping in mind that this may probably involves a significative computational time.

Another possible future use of this model is to get back what debated in *section 6.2* and to expand it through an optimization: it could be found for each path segment between two stops the optimal velocity profile, which may also consider all the constraints, such as speed limits, with a specific software; then, the best profile or a set of solutions could be simulated through the model to establish if they really brings improvements in energy consumption and to check that their adoption would not cause any problems with other variables like the line voltage. An optimization work could also consider the role of coasting and to apply profiles more complex than the simple ones partially seen, for example it could have accelerations huger at start which then reduce up to zero when cruise velocity is reached, to maintain the maximum power in reasonable limits. Nevertheless, also the passenger comfort should be an important constraint to consider.

The model could also be used to check what of the strategies listed at *chapter 4* is the best one for a given route. In this case, some new components should be declared but, above all, it would be necessary to have the complete data regarding the traffic and the consumption on that path, to be as precise as possible in obtaining results and in sizing the involved components. Then, it might be done an economic analysis to establish what is the best solution, because it is necessary to takes into account also this factor which cannot be considered negligible or marginal, considering the high costs of these components, which may be more elevated than the savings obtainable.

The model could be enhanced acting on some of its parts, for example the block oriented one: it could be partially modified to be closer to the classical model used for control, with the nested loops, fundamental in case of it should be used to study also the electric dynamics. However, it could bring even to a better force management, in fact, instead of evaluating the different powers and to sum up them to obtain the reference from which extract the current value, the resistance forces could enter in the controlled model as a disturbance of the required electric torque. Then, in a second time, the electric power could be obtained and added to the one of auxiliary services to find the current value. Moreover, even the auxiliaries could be deepened in order to reach a higher precision in results, considering the status of each component declared in MVB dataset and the corresponding power, besides it could also be taken into account the division between electric and pneumatic brake depending on the velocity, for a more exact estimation of regenerated energy.

Other possible modifications could be done to consider more trains per section or to expand the railway in its entirety as explained in *paragraphs 3.5.1* and *3.5.2*, for a better study of power flows and to have better results in case of availability of other trains data. Furthermore, this model, as already mentioned, might also be used to simulate an *AC/AV* railway; therefore, the needed changes could be done, in order to have a model as complete as possible, capable of simulating almost the totality of Italian rail system (with the only exclusion of diesel powered lines, which are totally different).

Finally, it could be created a user-friendly interface in order to simplify the usage of the model even to people which are not confident with Matlab and Simulink: this could be done using Matlab toolboxes specific for the creation of graphic interfaces and even applications, in the last versions. It could be similar to the one already developed for the block-oriented model, so with the possibility to choose the train model, its composition, the path that should be covered, moreover it could be added the possibilities to select a desired velocity profile or some recovery actions.

References

[1] https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[2] *Fast facts U.S. Transportation Sector Greenhouse Gas Emission*, U.S. Environmental Protection Agency (2018)

[3] Various Authors, *Climate Change 2014: Mitigation of Climate Change*, IPCC

[4] *2008 Guidelines to Defra's GHG Conversion Factors*, DEFRA

[5] Sara Khayyam, Ferdinanda Ponci, Javier Goikoetxea, Valerio Recagno, Valeria Bagliano, and Antonello Monti, *Railway Energy Management System: Centralized–Decentralized Automation Architecture*, IEEE (2016)

[6] T. Suzuki, B. Tech, *DC power-supply system with inverting substations for traction systems using regenerative brakes*, IEEE (1982)

[7] *La trazione elettrica in ferrovia*, Ministero Infrastrutture e Trasporti

[8] Giulio Bonifacio, *Creazione di un software per la simulazione del comportamento energetico di un veicolo ferroviario elettrico*, Tesi di laurea, Politecnico di Milano 2016

[9] Dario Baldi, *Sottostazioni reversibili nei sistemi ferroviari in corrente continua*, Tesi di laurea, Politecnico di Milano 2016

[10] Cristian Ferrini, *Voltage Oriented Control of an Innovative Bidirectional 3 kV Railway ESS using Parallel Three-Level NPC Converters*, Tesi di laurea, Politecnico di Milano 2017

[11] Alberto Minoia, *Dispense del "Corso di trazione elettrica"*, Università di Pavia

[12] *Prefazione Generale all'Orario di Servizio*, RFI (2007)

[13] Alessio Clerici, Enrico Tironi and Francesco Castelli-Dezza, *Multiport converters and ESS on 3 kV DC railway lines: case study for braking energy savings*, IEEE (2017)

[14] V. Calderaro, V. Galdi, G. Graber, A. Piccolo, A. Capasso, R. Lamedica, A. Ruvio, *Energy Management of Auxiliary Battery Substation Supporting High-Speed Train on 3kVDC Systems*, IEEE (2015)

[15] Alessio Clerici, Enrico Tironi and Francesco Castelli-Dezza, *Multiport converters and ESS on 3 kV DC railway lines: case study for braking energy savings*, IEEE (2016)

[16] Morris Brenna, Federica Foiadelli, Dario Zaninelli, *Bidirectional ESS for Railway Power Supply*, IEEE

[17] Z. Guiping, X. Mingchao, W. Siyu, *Hybrid Power Supply System of Rail Transit Based on On-board Energy Storage Equipment*, IEEE (2014)

[18] B. Mellitt, B.Tech, Z.S. Mouneimne, and C.J. Goodman, *Simulation study of DC transit systems with inverting substations*, IEEE (1984)

[19] Mihaela Popescu, Alexandru Bitoleanu, Vlad Suru, Alexandra Preda, *System for Converting the DC Traction Substations into Active Substations*, IEEE (2015)

[20] Pablo Arboleya, Bassam Mohamed, and Islam El-Sayed, *DC Railway Simulation Including Controllable Power Electronic and Energy Storage Devices*, IEEE (2017)

[21] Daniel Cornic, *Efficient recovery of braking energy through a reversible dc substation*, IEEE (2010)

[22] Hitoshi Hayashiya, Shinya Kikuchi, Kazushi Matsuura, Masami Hino, Masateru Tojo, Tetsuya Kato, Masato Ando, Takatoshi Oikawa, Mitsuru Kamata, Hiroshi Munakata, *Possibility of energy saving by introducing energy conversion and energy storage technologies in traction power supply system*, IEEE

[23] Shao-bo Yin, Li-jun Diao, Wei-jie Li, Rong-jia He, Hai-chen Lv, *On Board Energy Storage and Control for Inter-City Hybrid EMU*, IEEE (2017)

[24] Zhanguo Wang, Long Cheng, Jiuchun Jiang, *Research and simulation on energy storage system of dual power rail vehicle*, IEEE

[25] Ibrahim Sengor, Hasan Can Kılıc¸kıran, Huseyin Akdemir, Bedri Kekezoglu, and Ozan Erdinc¸ João P. S. Catalão, *Smart Railway Station Energy Management Considering Regenerative Braking and ESS*, IEEE (2017)