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Faculty of Electrical Engineering
Department of Electrical Power Engineering

High Speed Rail Electric-Power Supply Network

Diploma Thesis

Study programme:	Electrical Engineering, Power Engineering, and Management
Specialization:	Electrical Power Engineering
Diploma Thesis Supervisor:	prof. Josef Tlustý Ing., CSc.

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2. Trolley for high-speed railway
3. Electrical supply requirements for high-speed trains
4. Comparison of different types of supply systems

Bibliography/Sources:

[1] Doleček, R., Černý, O.: Trakční napájecí soustavy. UPCE, Pardubice 2015.
[2] Steimel, A.: Electric Traction: Motive Power and Energy Supply. Deutscher Industrieverlag GmbH, Berlin, 2014.
[3] Materiály výrobců trakčních zařízení.

Diploma Thesis Supervisor: prof. Josef Tlustý Ing., CSc.

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Prague, April 1, 2016

Declaration

I declare that I have worked on my diploma thesis titled "High Speed Rail Electric-Power Supply Network" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

In Prague on 27.5.2016   …………………………

Acknowledgement

I would lid to thank to the powerful minds for their great intelligence capable of understanding the complexness of technology, to plan and shape systems in order to improve the standard of living of humankind and other living entities.

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Elektrické napájení vysokorychlostních vlaků

Souhrn

Vysokorychlostní doprava zažívá celosvětově nevídaný rozkvět a růst. Potřeba velké přepravní kapacity ve světě vede k diskuzi o omezení emisí oxidu uhličitého. Jako řešení se jeví vyšší využívání železniční dopravy, která je ekologičtější. Vysokorychlostní vlaky šetří čas při meziměstském cestování. Tato diplomová práce se zabývá konvenčními a vysokorychlostními vlaky, o jejich hlavních charakteristikách a technologii od počátku historie železniční dopravy. Dále jsou vysvětlené výhody a nevýhody každého napájecího systému, zejména z hlediska energetické účinnosti.

Tato práce se také zabývá vysokorychlostními vlaky, mechanikou trakčního vedení, úbytky napětí a energetickými ztrátami na tomto vedení. V další části práce je zhodnocena spolupráci mezi vlaky a trakčním vedením a to zhlediska technické, ekonomické stránky a budoucnosti interoperability napájecích stanic v Evropě.

Byly vypočteny parametry různých zařízení, od napájecích stanic přes trolejové vedení, nosné lano, zesilovací vedení a koleje až do vlaku. Veškerá potřebná data byla získaná od společnosti SIEMENS. K vypracovaní výpočtů byl použit MS excel.

Klíčová slova: Vysokorychlostní železnice, Vysokorychnlostní vlak, Konvenční vlak, Elektrická trakce, Trakční vedení, Pantograf, Trakční pohon, Trakční transformátor, Elektrické vozidlo, Elektrický napájecí systém

High Speed Rail Electric-Power Supply Network

Summary

Globally, the high-speed rail industry is experiencing enormous and speedy growth. Worldwide traffic overcrowding and discussion over carbon emissions are making several nations to review their transportation policies and turn to an increasing extent to rail. High-speed trains are especially effectual at removing stress off short-haul flights and bringing cities closer with each other. This research deals with an overview of Conventional and High-Speed Trains, it talks about the main characteristics and the technological implementation and its progress from the beginning of history. Attempt has been made to explain the advantages and disadvantages of each type of OCL, then its comparison in terms of energy efficiency.

Furthermore an investigation of the characteristics requirements of High-Speed Trains, it's catenaries mechanics, the behavior of the Voltage Drops and the Power Losses generated by them have been discussed. The symbiosis between Trains and Overhead Contact Line, the future of Power Supply for European interoperability, with the aim to reach an effective performance in technical and economic terms were critically analyzed.

The calculation of the various parameters forming the whole system, from the Power Substation, through the Catenary, Trolley, Rail and Feeder line, to the Train, were gotten from field data's of SIEMENS s.r.o, company. Microsoft Excel software package was then used to analyze research finding.

Keywords: High-speed rail, High-speed trains, Conventional trains, Electric traction, Overhead Contact Line, Pantograph, Traction motors, Traction transformers, Rolling stock, Electric-power supply network.

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List of Symbols

Symbol	English denomination	*Czech denomination*	Units
U_n	Nominal Voltage	*jmenovité napětí*	kV
I_n	Nominal Current	*jmenovitý proud*	kA
P_n	Nominal Power	*jmenovitý výkon*	MW
N	Number of units	*počet soustrojí*	-
P_{cn}	Total Nominal Power	*celkový jmenovitý výkon*	MW
S_{TW}	Trolley Wire Section	*průřez Troleje*	mm^2
p_{oTW}	Trolley Wire wear out	*Opotřebení Troleje*	%
ρ_{TW}	Trolley Wire Resistivity	*měrný odpor Troleje*	Ωmm^2/m
S_{FL}	Feeder Line Area	*Průřez Zesilovacího Vedeni*	mm^2
p_{oFL}	Feeder Line wear out	*Opotřebení ZV*	%
ρ_{FL}	Feeder Line Resistivity	*měrný odpor ZV*	Ωmm^2/m
S_{CW}	Catenary Wire cross section	*Průřez nosného lana*	mm^2
p_{oCW}	Catenary Wire wear out	*Opotřebení NL*	%
ρ_{CW}	Catenary Wire Resistivity	*měrný odpor NL*	Ωmm^2/m
Δt	temperature difference	*oteplení*	K
α	Temperature coefficient	*teplotní součinitel odporu*	K^{-1}
∇R_{TW}	Resistance gradient (RG) TW	*gradient odporu T*	mΩ/km
∇R_{CW}	Resistance gradient (RG) M	*gradient odporu NL*	mΩ/km
∇R_{FL}	Resistance gradient (RG) CW	*gradient odporu ZV*	mΩ/km
∇R_{TW}	GR of the Trolley Wire	*gradient odporu troleje*	mΩ/km
∇R_{CW}	GR of the Catenary wire	*gradient odporu nosného lana*	mΩ/km
∇R_{FL}	GR of the Feeder line	*gradient odporu zesilovacího vedení*	mΩ/km
∇R_{OCL}	GR of the Overhead Line	*gradient odporu vrchního vedení*	mΩ/km
∇m	Mass gradient	*gradient hmotnosti*	kg/m

ρ_m	Mass density	*měrná hmotnost*	kg/dm^3
S_k	Side section of the rail	*průřez koleje*	mm^2
f	Frequence	*frekvence*	Hz
μ	Permeability	*permeabilita*	H/m
μ_r	Relative permeability	*relativní permeabilita*	-
x	Skin depth	*hloubka vniku*	mm
p	Perimeter	*obvod*	mm
d_v	Conductive area	*vodivý průřez*	mm^2
ΔR_K	Increase of resistivity	*zvýšení odporu*	%
∇R_{AC}	AC GR	*gradient odporu AC*	mΩ/km
∇R_G	Ground GR	*gradient odporu zemního tělesa*	mΩ/km
∇R_{RL}	Return wire GR	*gradient odporu zpětného vedení*	mΩ/km
r	Radius of the conductor	*poloměr vodiče*	mm
H	Height of the conductor	*výška vodiče*	m
∇L	Inductance gradient	*gradient indukčnosti*	mH/m
∇X	Reactance gradient	*gradient induktivní reaktance*	mΩ/km
∇Z	Impedance gradient	*gradient impedance*	mΩ/km
$\cos\varphi_{OCL}$	Power factor of the OCL	*účiník vedení*	-
φ_{OCL}	Phase angle of the OCL	*fázový úhel vedení*	°
l	Length the section	*délka úseku*	km
n_{IN}	Supply points	*stran napájení*	-
∇R_{TR}	Total GR	*výsledný gradient odporu*	mΩ/km
P_T	Traction Power	*trakční výkon*	kW
η_{PT}	Efficiency of the Traction drive	*účinnost trakčního pohonu*	%
P_{AUX}	Auxiliary drive	*pomocné pohony*	kW
P_H	Heat	*topení*	kW
P_C	Total input power	*příkon celkem*	kW
U_{nV}	Nominal Voltage of the vehicle	*jmenovité napětí vozidla*	V
I_{IN}^{*}	Current collected by the vehicle	*vozidlem odebíraný proud*	A
$\cos\varphi_V$	Power Factor of the vehicle	*účiník vozidla*	-
φ_V	Phase angle of the vehicle	*fázový úhel vozidla*	°
I_{IN}	Current collected by the vehicle	*vozidlem odebíraný proud*	A
$R_{l/2}$	R in the middle of the section	*odpor vedení uprostřed úseku*	Ω

$X_{l/2}$	X in the middle of the section	*reaktance vedení uprostřed úseku*	Ω
$Z_{l/2}$	Z in the middle of the section	*impedance vedení uprostřed úseku*	Ω
$R_{n/2}$	R of PS in the middle of the section	*odpor napájení uprostřed úseku*	Ω
$X_{n/2}$	X of PS in the middle of the section	*reaktance napájení uprostřed úseku*	Ω
$Z_{n/2}$	Z of PS in the middle of the section	*impedance napájení uprostřed úseku*	Ω
$cos\varphi_n$	Power factor of the Power Supply	*účiník napájení*	-
φ_{Zn}	Phase angle of the Power Supply	*fázový úhel impedance napájení*	°
ΔU_{nIN}	Voltage drop of the Power Supply	*úbytek napětí napájení*	V
$\varphi_{\Delta U}$	fázový úhel úbytku napětí	*fázový úhel úbytku napětí*	°
U_{nIN}	Voltage at the feeding point	*napětí v místě odběru*	V
U_{inL}	Voltage at the feeding point with Load	*napětí na výstupu měnírny zat..*	V
U_{inNL}	Voltage at the feeding point without Load	*napětí na výstupu měnírny napr.*	V
$U_{l/2}$	Voltage at the middle of section	*napětí uprostred vedeni*	V
I_{1s}	One-side driven current	*proud přiváděný proud*	A
ΔU_{OCL}	Active Voltage drop at the OCL	*činný úbytek nap. na vrchném ved*	V
ΔU_R	Active Voltage drops at the Rail	*činný úbytek napětí na kolejnici*	V
$\Delta U_{\frac{l}{2}}$	Active V drop in the middle of the section	*činný úbytek napětí uprostřed*	V
$P_{\frac{l}{2}}$	Active Power at the middle of the section	*činný výkon uprostřed úseku*	kW
$\Delta P_{\frac{l}{2}}$	Power Loss at the middle of the OCL	*ztráty ve vedení uprostřed*	kW
P_{nIN}	Active Power of the Power Supply	*činný výkon napájení*	kW
$\eta_{l/2}$	Efficiency at the middle of the OCL	*účinnost vedení uprostřed úseku*	%
$p_{l/2}$	Power Loss density at the middle of the OCL	*měrné ztráty uprostřed*	%

ΔP_{AV}	Average Power Loss	*ztráty střední*	kW
P_{AV}	Average Power	*výkon střední*	kW
η_{lAV}	Average Efficiency of the OCL	*účinnost vedení střední*	%
p_{AV}	Average Power Loss density	*měrné ztráty střední*	%
p_{PAV}	Average Power Loss	*měrné ztráty střední k výkonu*	%

List of Abbreviations

AC	Alternate Current
DC	Direct Current
CT/CR	Conventional-Train / Conventional Rail
HS	High-Speed
CTI	Conventional-Train Infrastructure
HSI	High-Speed Infrastructure
IT	Independent traction
SIT	Semi-independent traction
DT	Dependent traction
GTO	Gate Turn-Off Thyristor
IGBT	Insulated-gate bipolar transistor
RENFE	Spanish National Railway Network / *Red Nacional de los Ferrocarriles Españoles*
DB	*Deutsche Bahn*
WWII	Second World War
DCS	Direct Current Substation
ACS	Alternate Current Substation
TSP	Traction Sectioning Point
OCL	Overhead Contact Line
BT	Booster Transformer
AT	Auto-Transformer
FACTS	Flexible AC Transmission System
SVC	Static VAr Compensator
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
RAB	Rail Active Balancer
EMC	Electromagnetic Compatibility
4QR	Four-Quadrant Rectifier

PWR	Power-Width Regulator		
RB	Regenerative Braking		
TW	Trolley Wire		
CW	Catenary Wire	*NL*	*Nosné Lano*
FL	Feeder Line	*ZV*	*Zesilovací Vedení*
GR	Gradient Resistance		

1   Introduction

The transportation demand for people and goods around the world is experiencing a huge growth, this goes hand-in-hand with the increasing population of people, thereby making cities over-crowded. Hence, a lot of requirements is needed to satisfy transportation users in this circumstance, these include; comfort, velocity of traveling, and other technical aspects, which can help in a tremendous way, not only for the users to get to the desired destination in a record time, but also the integration of regions to create a socio-economically balanced society. This entails the strengthening and construction of new and more global infrastructure of high-speed trains. This cannot be achieved without significant demand in areas of investment, technology, industry, environmental, social and political aspects of human life [1], and [2]. Today, there is high development of high-velocity rail transportation system in France and Japan Germany, Switzerland, England, Italy, Finland and Sweden. And as time goes by, there is a build-up of high-speed rail networks connecting many cities in Europe. The high-speed rail transportation system has brought optimal solution to the transportation industry as compared to the current aerial and terrestrial transport system [3], [4], [5] and [6].

The European idea of the future high speed rail consist of continental network construction called "Interoperable", it is the ability of the trans-European high-speed rail network to allow the flow of high-speed trains fulfilling the requirements for comfort, security, quality and reliability of its functions. In order to fulfill this objective, it is obligatory to apply technical and operational acceptance. The political resolutions of European countries pertaining to issues of standardization of the high-speed transportation networks crossing different types of environmental conditions, civil constructions such as tunnels or bridges, and respecting local standards of every state involved. Requires dimensioning of the tracks, documentation, geometrical parameters, signalizations, systems security, electrical supply, levels of Voltage, frequency, etc., all these have to be standardized. The main solution to these problems is implementation of power supply system voltage level for these type of trains [6], [7], [8], [9], and [10]

This research work analyzes the behavior of various types of power supply systems used in high speed rail networks, this is done in order to choose the one with the highest advantages and make effort to increase the quality. High-Speed trains are designed to operate at speeds up to 320 km/h. These trains are usually called "unconventional", it helps to reduce environmental pollution due to its non-dependence on fossil fuels. This will in the future reduce the flow of airplanes in the continents of Europe and Asia, and eventually in the whole of America and Africa as well, thereby leaving aerial traveling mainly for transoceanic transportation.

2   Objectives and Methodology

2.1 Objectives

The main objective of this study is the comparison of the trends and implementation of AC and DC power supply systems for conventional and high-speed trains.

The specific objectives of the study were as follow:

i. To investigate the effect of power transmission quality on Overhead Contact lines of high speed trains.

ii. To investigate the electric-power properties of Rolling stocks of high speed trains.

iii. To investigate the implementation process of high speed train technology.

2.2 Methodology

In other to study the comparison of the trends and implementation of AC and DC power supply systems for conventional and high-speed trains, both primary and secondary data were used. To investigate the effect of power transmission quality on Overhead Contact lines of high speed trains, the electric-power properties of Rolling stocks of high speed trains, and the implementation process of high speed train technology, the characteristics requirements of High-Speed Trains, the mechanics of its catenaries, the behavior of the Voltage Drops and the Power Losses generated by high speed trains were used as a measure. The Primary data was obtained from SIEMENS s.r.o, while the secondary sources used included information on high speed rail power system technology obtained from journals, periodicals, textbooks, dissertations, abstracts, magazines, newspapers etc.

3 Literature Review

3.1 The Trains

The aim of this chapter is to take a brief overview of the Rolling Stocks, its classification according to power supply and applications, its technologies and most importantly its components, and the parameters used for calculations in further chapters.

3.1.1 Classification of Trains

Electrically, we can classify trains taking into account few parameters. For example, the type of current it consumes: AC, DC or Multi-system units. Another point is the way the traction is supplied: Independent, Semi-independent and Dependent [11], [12] and [13].

3.1.1.1 *Types of Electric Traction*

3.1.1.1.1 Independent traction (IT)

This type of traction does not need any connection to the electrical grid. It has an internal combustion fuel engine as described in *Figure 1* [14].
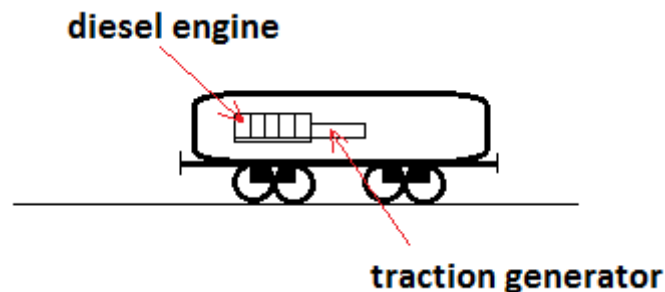
Figure 1 - Independent electric traction
(Source: Authors own work)

3.1.1.1.2 Semi-independent traction or Hybrid vehicle (SIT)

The type of train, described in *Figure 2*, contains a set of accumulators which evidently need to be charged after every use. These trains do not need a great investment of infrastructure but on the other hand, it is required to be equiped with batteries, they are considered the most unreliable and expensive type of electrical supply source powered trains [15].
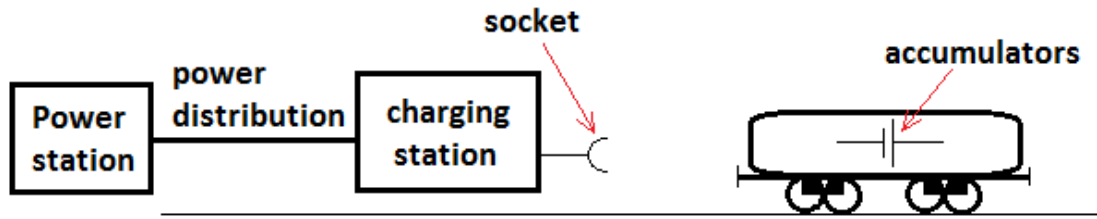
Figure 2 - Part-dependent electric traction

(Source: Authors own work)

3.1.1.1.3 Dependent traction (DT)

This is the most important type of electric traction. In this type of traction system the train needs to be connected directly and constantly to a substation for its power supply, firstly it is connected through the **overhead line** which is in contact with the **current collector,** or most commonly called **pantograph collector** [16], a graphical description is shown in *Figure 3*.
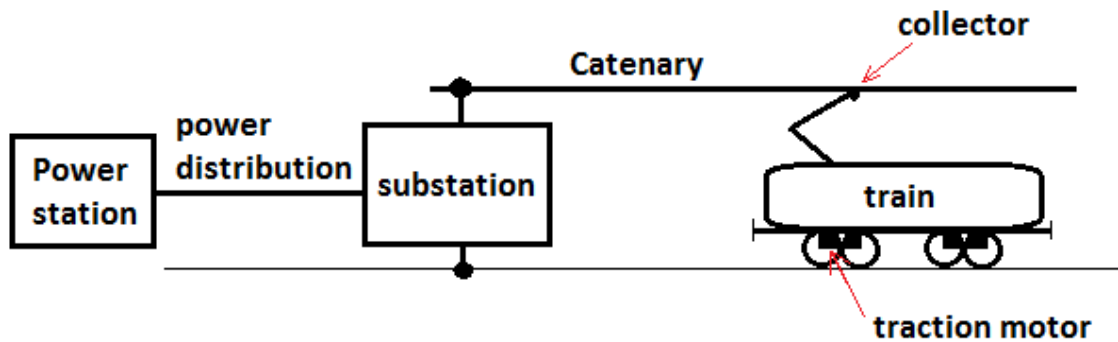
Figure 3 - Dependent electric traction

(Source: Authors own work)

3.1.1.1.4 Comparison of the DT, IT, and SIT

The main merits of trains with DT is that they are simple since it has only one type of energy conversion system, that is from electrical to mechanical, which makes it cheaper, lighter and thus can reach higher power (power density up to 80kW/T). On the other hand, the IT has 3 types of conversion of energy inside the wagon, first, is the combustion of fuel for mechanical work, second, is conversion of mechanical energy to generate electrical energy, and electrical to mechanical energy. Based on this principle it can be say that the IT system, is more expensive and complex and thus heavier, which gives us a less powerful system (Power density up to 25kW/T). In terms of infrastructure, the DT requires a more complex system (electrical power supply and transmission, substations, utility poles, overhead lines and so on), when IT only needs a very simple infrastructure. For these reasons, it can be siad that from economical point of view, the DT system has a high fixed cost (that is the cost of infrastructure) and a low variable cost (that is cheap cheap electrical energy). The IT system has a low fixed cost

(meaning no complex infrastructure) but a higher variable cost (that is expensive fossil fuel) [14], [15], and [16].

For optimal implementation of any of these systems, we have to take into account many other factors, such as the distance and the amount of passengers who will travel from any point A to point B. The IT is favorable in case of lower traffic, and in the case of a dense traffic, the DT is more advantageous.

In the economic perspective, we can calculate the cost of each system:

IT:

$$H = 10\frac{kWh}{dm^3}, \quad c_n = 28\frac{kč}{dm^3}, \quad \eta = 0,4 \cdot 0,8 = 0,32 \tag{1}$$

Where: H .... Heat of combustion

                  c_i .... Price of the fuel

                  η_i .... Efficiency of the diesel vehicle

From this we obtain the total cost of energy per hour of the IET:

$$c_{ti} = \frac{c_i}{\eta_i \cdot H} = \frac{28}{0,32 \cdot 10} = 9 \; Kč/kWh \tag{2}$$

DT:

$$c_d = 2,1\frac{kč}{kWh}, \quad \eta_d = 0,82 \cdot 0,85 = 0,7 \tag{3}$$

Where: c_d .... Price of the electrical energy

                  η_d .... Efficiency of the electrical vehicle

From this we obtain the total cost of energy per hour of the DET:

$$c_{td} = \frac{c_d}{\eta_d} = \frac{2,1}{0,7} = 3 \; Kč/kWh \tag{4}$$

SIT:

$$c_{pd} = 2,1\frac{kč}{kWh}, \quad \eta_{pd} = \eta_m \cdot \eta_b \cdot \eta_c = 0,9 \cdot 0,7 \cdot 0,8 = 0,5 \tag{5}$$

$$c_b = 5000\frac{kč}{kWh}, \quad N = 1000 \tag{6}$$

Where

c_{pd} ..... Price of the electrical energy

η_m ...... Efficiency of the motors

η_b .... Efficiency of the batteries

η_c .... Efficiency of the converters

η_{pd} ..... Efficiency of the electrical vehicle

c_b .... Price of the batteries

η_{bd} ..... Depth of discharge

N .... Number of cells

From this we obtain the total cost of energy per hour of the DET:

$$c_{tp} = \frac{c_{pd}}{\eta_{pd}} + \frac{c_b}{\eta_{bd} \cdot N} = \frac{2,1}{0,5} + \frac{5000}{0,8 \cdot 1000} = 10 \; K\check{c}/kWh \tag{7}$$

From equations (1) - (7), we can say that the DT is the less expensive option, in terms of energy consumption. Due to the vailability of modern electronics, currently working High-speed trains are so called **Multi-system units**. This type of units can operate at a variable railway electrification system. The overhead wires can change to any level of voltage (from 1.5 to 25 kV) or any type of current (DC or AC). Fortunately, the trains do not have to stop when passing from one system to another, the train only moves with no power for a few seconds [14], [15], and [16].

3.1.1.2 *Type of trains considering the electric supply*

Thanks to the modern electronics, currently working High-speed trains are so called **Multi-system units**. This type of units can operate at a variable railway electrification system. The overhead wires can change to any level of voltage (from 1.5 to 25 kV) or any type of current (DC or AC). Fortunately, the trains don't have to stop when passing from one system to another, the train only moves with no power for a few seconds.

3.1.1.3 *Type of trains considering their application*

- Main Land Trains
- Urban Trains
- Underground
- Mining Trains
- Industrial Trains
- Highway Trolley Bus

In this classification, it is necessary to take to account some parameters, for example, the distance between the stops or stations and the permitted speed of each of them. In the case of Urban Trains, in Prague, specifically Trams, stops have an average distance about 500m between each other [17], with an average speed of 19 km/h, which means that it has to be designed for a more constant sequence of braking-accelerating. In the case of Underground trains, the distance comparing to Trams is twice larger, this, for instance, means a lower braking-accelerating sequence, but the velocity varies about 35.7 km/h.

In the case of Main Land Transportation, the average distance between stops is not defined, it can be of many kilometers and the velocity can vary according to the type of Train, for Conventional types around 160 km/h and for HS 250 km/h approximately.

3.1.2 The electrical system of the vehicle

To define the electrical system of a Rolling Stock, first of all, we have to classify them according to its equipment. There are three categories: **The main tractive devices** which can be electrical motors, hydrodynamic with electrical and electronic controls, secondly, **the auxiliary tractive devices** such as ventilators, compressors, and pumps. And finally, **another type of devices** such as batteries, illuminating, heating, air conditioning, doors, control system and so on. When the train is in contact through the pantograph to the catenary, it gets the energy from the net and transforms it into at least 3 levels of voltages. The highest level of voltage inside the wagon is normally around three-phase 400V or 380V, which is used to supply the main tractive devices (driving motors) and other big equipment such as the compressor, main ventilation system or pumps. Another level of voltage, commonly used is the single-phase 230V / 110V (50 / 60 Hz) for small devices, such small fans, illumination or sockets for the passengers. There is also necessary to supply DC current to the information system, control system, illumination and other DC devices. The level of voltage can vary from 24V up to 100V DC, depending on the requirements of the client **Chyba! Chybný odkaz na záložku.** shows the diagram of a modern AC Train.

Figure 4 - Diagram of a modern AC Train

(Source: Authors own work)

The historical advantage of DC systems was the use of DC motors, directly connected to the overhead traction line. This advantage is not taken into account anymore, practically all the vehicles fabricated after 1990 use AC Traction Motors, mechanical commutator was replaced by a static commutator, connected through semiconductor converters. *Figure 5*, illustartes the block diagram of a DC and AC connection of the vehicle to the grid
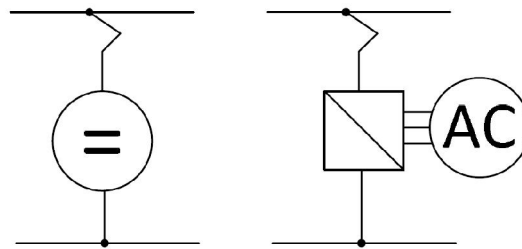
Figure 5 - Block Diagram of DC and AC connection of the vehicle to the grid
(Source: Authors own work)

3.1.2.1 *The pantograph*

The pantograph is the apparatus assembled on the top of the train and is the responsible for the current collection of the electric vehicle from the catenary wire. Generally, a single phase is connected with the pantograph and the return wire is connected to the track.

The pantograph is operated by compressed air from the braking system. This system pushes the pallets that can be seen in *Figure 6*, most of them made of metal-carbon strip, which reaches the contact wire so the vehicle can draw electricity for running. The material used for this part of the pantograph and its geometrical dimensions are also really important parameters considered for interoperability standards.
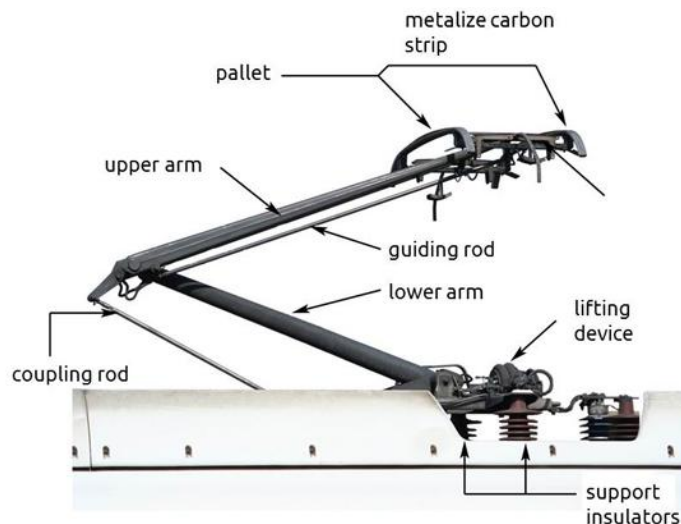
Figure 6 - Train's Pantograph **[18]**

The issues that might take place when the pantograph is disconnected or the switching off of the main circuit breaker will be explained in point 3.2.3.2.

3.1.2.2 *Traction Transformers*

Traction transformers are dimensioned according to the established levels of operating voltage, (1.5, 3, 11.5, 15 or 25kV, or other special levels), capacity up to 10MVA and above. In the case of AC connection, it can be designed for a frequency from $16 \frac{2}{3}$ to 60Hz. They can also have a configuration for multiple operations, so they can work on more than one level of voltage and type of connection. Transformers are designed to be positioned under the wagon as seen in To define the electrical system of a Rolling Stock, first of all, we have to classify them according to its equipment. There are three categories: The main tractive devices which can be electrical motors, hydrodynamic with electrical and electronic controls, secondly, the auxiliary tractive devices such as ventilators, compressors, and pumps. And finally, another type of devices such as batteries, illuminating, heating, air conditioning, doors, control system and so on. When the train is in contact through the pantograph to the catenary, it gets the energy from the net and transforms it into at least 3 levels of voltages. The highest level of voltage inside the wagon is normally around three-phase 400V or 380V, which is used to supply the main tractive devices (driving motors) and other big equipment such as the compressor, main ventilation system or pumps. Another level of voltage, commonly used is the single-phase 230V / 110V (50 / 60 Hz) for small devices, such small fans, illumination or sockets for the passengers. There is also necessary to supply DC current to the information system, control system, illumination and other DC devices. The level of voltage can vary from 24V up to 100V DC, depending on the requirements of the client Chyba! Chybný odkaz na záložku. shows the diagram of a modern AC Train.
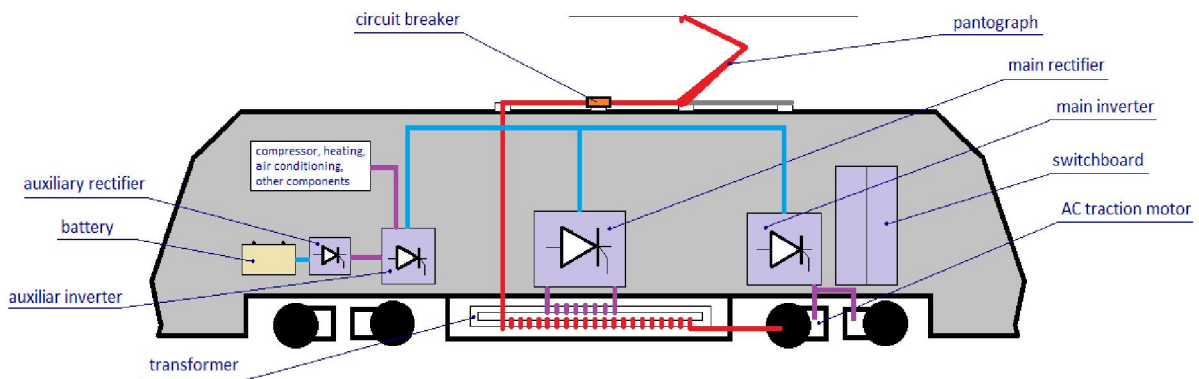
Figure *4*. The material used for cooling can be mineral oil, silicone or Ester fluid, according to the customers and the environmental requirements.

Figure 7 - SNCF Tram line T4, Paris [19]

For example, as it is seen in *Figure 7* the SNCF Tramline T4 fabricated by Siemens, has a rated power of 690kVA and operates at 750 V DC or 25kV/50Hz.

3.1.2.3 *AC Traction Motors*

At the beginning of the development of electrical transport, DC motors were preferred, because of the simplicity of controlling its velocity. Nowadays, with the appearance of power electronics in the 80's and its development, with the help of microprocessors, it became easier to control velocities, traction, and adhesion of AC motors. The principle, in a simple explanation, is to regulate the stator's current components of torque and flux. AC Traction Motors are also commonly called *Asynchronous motors* or *Induction motors*. At a first sight DC and AC motors look very similar, but studying them in a more profound way, we can find out that AC motors have a simpler construction, without some mechanical contacts, that means no brushes. Therefore, we have a machine of the same power but lighter than DC motors. Another characteristic of the AC motor comparing to the DC type is that they are more robust, more reliable and maintenance is easier.

3.1.2.4 *Inverters and Rectifiers*

Power electronics has been applied for the control of asynchronous machines more than 20 years now. First, current inverters composed of thyristors were available, those at the same time, needed to be equipped with commutation circuits in order to function properly. In the 80's the application of GTO simplified the existing inverters; this meant also the volume and weight reduction, increasing the reliability of the system. In the 90's, after a really short time, the GTO technology was replaced by the IGBT, bringing with its many advantages, because, being it a voltage controlled semiconductor device, it has an easier gate drive. It has very low switching losses and, therefore, there is no need of any power loss snubber circuit, which means

a reduction of the robustness of the system, this also brings a reduction of the cooling system [20].

Just to give some examples, the inverter for the Spanish locomotive RENFE S 252, from 1991, 2,7MW, 4,5kV composed with GTOs, it is 5600mm long and 4,7t weight with a choke circuit about 1t heavy, comparing it with the EuroSprinter Class 189 from 2003, 3,2MW, 6,5kV composed of IGBTs, it is 3300mm long with a weight of the only 3t, and comparing it with the first shown in this paragraph, the second one doesn't need a pulse modulator in the input. Another advantage is the possibility of functioning with a higher switching of frequency (3 to 4 times) [20] making achievable to reduce the harmonic losses in the motor.

The inverter used in the EuroSprinter Class 189 described in *Figure 8* is connected to the catenary, the transformer reduces the level of voltage of the AC power supply and an AC-DC converter, most known as 4QR, which is also used to create a DC bus for the IGBTs blocking voltages. In DC systems, the overhead line connected directly to the DC link. This topology uses a DC link voltage of 1800V with a blocking voltage of 3300V. [21]
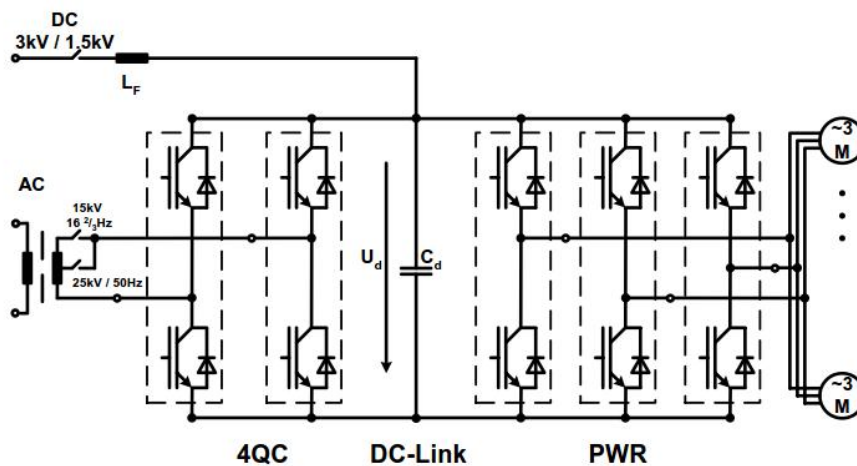
Figure 8 - Chopperless Multiple System converter for the DB BR 189 **[22]**

In the case of High-Speed trains, cascades IGBT modules are used. In *Figure 9*, we can see the topology developed by the company Alstom, It consists of eight modules of 6.5kV each connected to 15kV 16 ⅔ Hz.
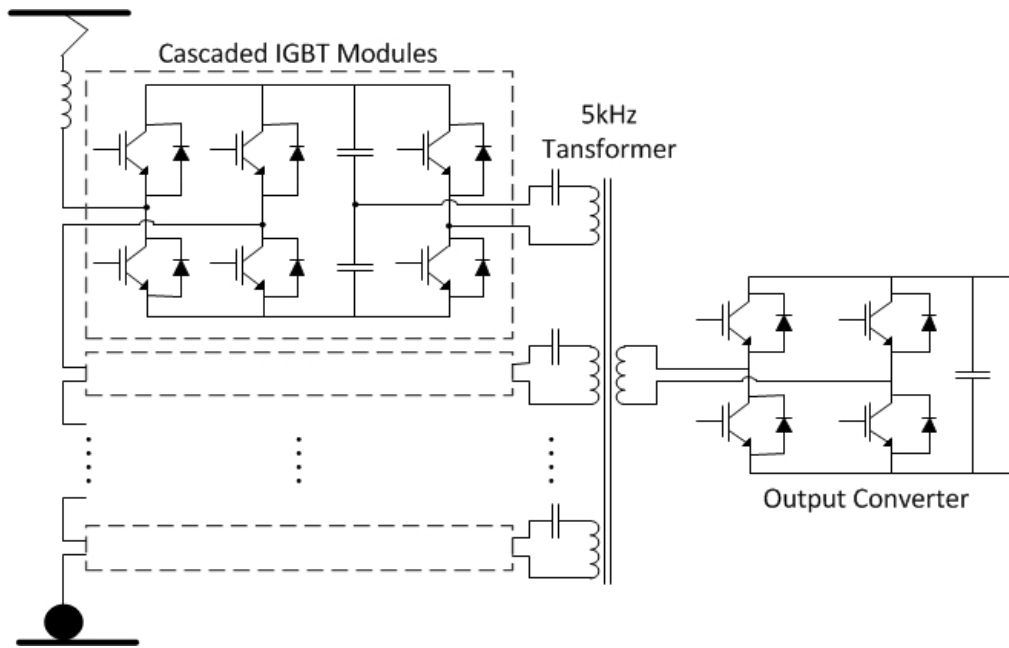
Figure 9 - Topology of the Cascade Modules for High-Speed Trains **[21]**

3.2 The Overhead Contact Line

The railway electrification system is the responsible for the transmission of electrical energy from the distribution to the catenary. The electrical supply can be classified according to the design (contact system of one, two or three conductors, fourth and third rail), the level of voltage and the type of current (AC, single or three phase, and DC current). In the case of AC, the frequency takes place as well.
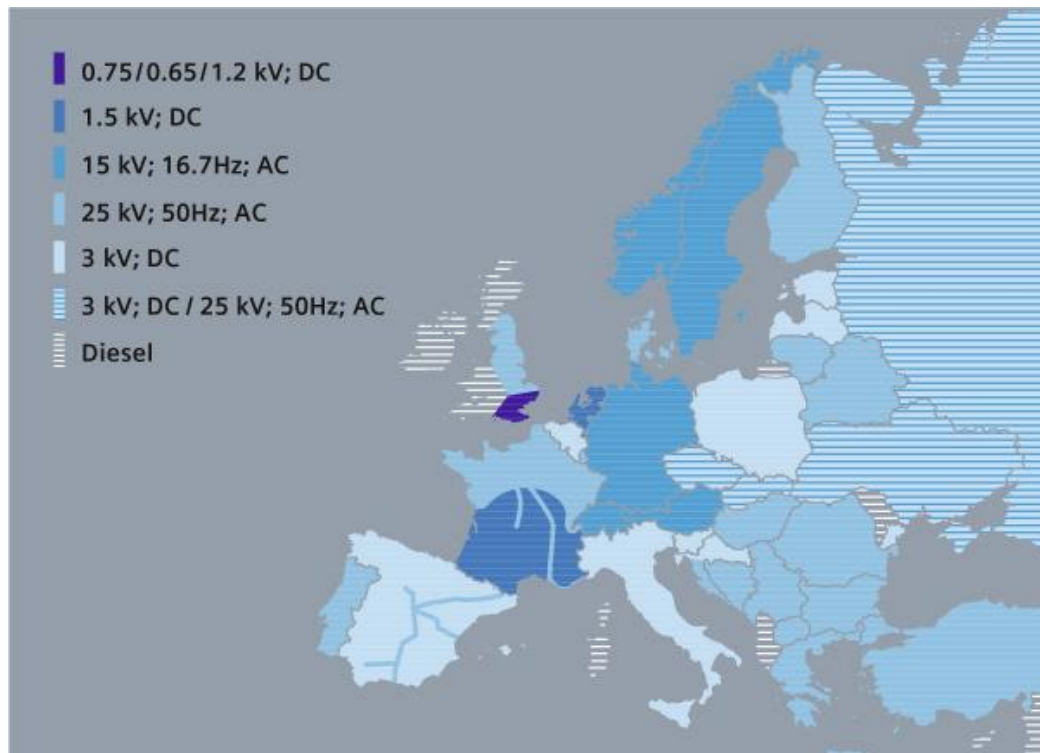
Figure 10 - Map of the railway electrification systems in Europe [11]

In the beginning of the electrification of rolling stocks, every company was developing their own system for the electrical supply, they implemented the one they considered as more convenient. The appearance of each system through time is shown is *Figure 11*. The first who standardized were the German-speaking countries –Germany, Austria and Switzerland. After the WWII, the revolution of the superconductive materials took place and with that, the possibility to work with a frequency of 50Hz, which brought the implementation of the second type of electrical supply. The main difference between the electrical supply system AC and DC is not only the existence of a frequency or the levels of voltage, but it is mostly about the infrastructure. DC systems require the installation of a **DC Substation** (DCS) and for the AC systems an **AC Substation** (ACS). The conjunction of these two types of

systems makes necessary the installation of a combined system. In the sections between the electrical supplies, we might install so-called **Traction Sectioning Point** (TSP). [23]
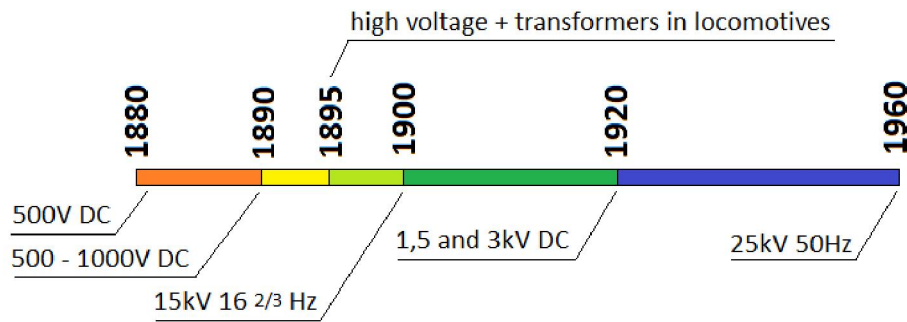
Figure 11 - Timeline of the Railways supply systems

(Source: Authors own work)

These TSP help to increase the reliability of the overhead lines and the power of the traction devices installed on the substations, and, at the same time, they separate the catenary wires into sections. The biggest advantages given by these stations are at first, to decrease the power losses and secondly, to decrease the drop voltages in the railway electrical wiring.

3.2.1 Classification of OCT

3.2.1.1 *Direct Current Systems*

3.2.1.1.1 **<1kV DC**

- *250V DC: for Mining Rail Systems*
- *600V DC: for City Transportation*
- *750V DC: for Underground Railways (Metro)*
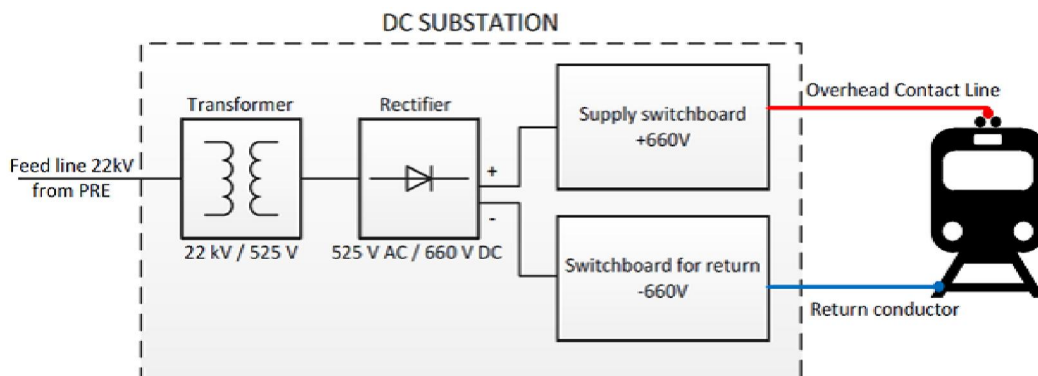
Figure 12 - Simplified diagram of a DC Substation for the supply of a 660V DC Tram line

(Source: Authors own work)

This system consists of a DC Substation connected to the distributor, in the Czech Republic usually 22kV as is shown in *Figure 12* this level of voltage is then transformed to a

lower level about 525V which is then connected to a six (*or twelve*) pulse bridge rectifier, which supplies the overhead contact line to a 660V DC. Usually, the connection of the OCL is made with cables and for the return, the rails are used as conductors. In the case of tram lines, the positive pole is connected to the OCL and the negative one to the rail. In the case of Underground Railways or S-train, the third rail is applied.

3.2.1.1.2 1,5kV DC

Main Application: Mainland and Industrial Transportation System

This system was developed in the 30's; it is still used in countries as France and Netherlands and is currently considered to have many disadvantages. In the Czech Republic, the connection between cities Tábor and Bechyně this system is still functioning. The topology of the substation is similar to the 750V DC shown in *Figure 12*.

The low value of DC level facilitates the dissipation of the electric arc caused by short circuits and thus, fewer requirements for isolation. [24]

3.2.1.1.3 3kV DC

Main application: Mainland Transportation

This system is mainly used in countries as Belgium, Italy, Poland, Czech, Slovakia, Russia, Ukraine, Slovenia and Spain. In comparison with the other DC systems, there are not so big differences on infrastructure. In terms of power load, the 3kV DC system allows having a high load power and lower losses in the catenary. This makes less necessary to provide a feeding line. It is more complicated in terms of isolation, protection of overvoltages during transient states and the extinguishing of electric arcs when turning off. The sections are usually connected from two sides, each side to a DC substation. One of the characteristics of this supply system is the installation of DC substation approximately each 20km.

3.2.1.2 *Alternate Current Systems*

3.2.1.2.1   15kV 16 ⅔ Hz

This system is mainly used in German speaking countries as Switzerland, Germany, Austria and Nordic countries as Norway and Sweden. The improvement of the single phase commutation motor in the beginning of 20th century made possible the development of the single-phase railway system. Decreasing the frequency to ⅓ of the grid frequency, they got to the value of 16 ⅔ Hz, logically, the three phase railway system was completely deflected after this advancement.

The main reasons for this particular frequency were the satisfactory commutation of commutative traction motors (with the laminated stator core, compensation winding and with phase shifted auxiliary poles). Thanks to this frequency the transformed voltage in the commutated winding decreased about 1/3 as is shown in the Equation *(8)*, also the voltage drop caused by the inductive reactance X_L decreased according to Equation *(9)*.

$$U_t = \frac{d\Phi}{dt} = k \cdot f \cdot \Phi \tag{8}$$

$$\Delta U = X_L \cdot I = 2\pi \cdot f \cdot L \cdot I \tag{9}$$

When this system is connected to a 3-phase AC 50Hz supply, it has to be connected to a converter. Historically, this frequency converter was a high-frequency motor or motor-generator set, it consists of a six-pole 3-phase synchronous motor or two-pole single-phase synchronic generator. Now, with the semiconductor devices this frequency was corrected to 16,7Hz ($\neq$ 16 ⅔Hz) to avoid resonant effects.
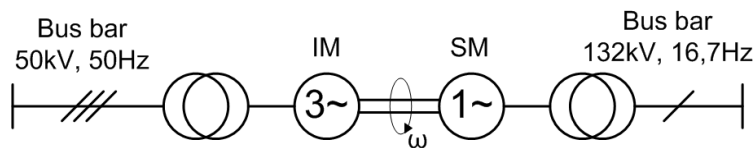
Figure 13 - Topology of the Motor-generator set

(Source: Authors own work)
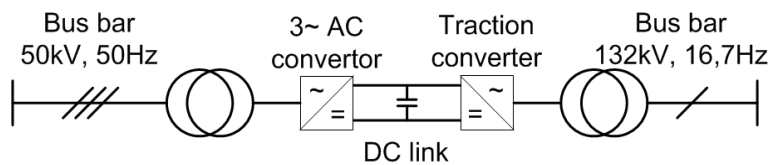
Figure 14 - Topology of the Static Frequency converter

(Source: Authors own work)

The 15kV 16,7Hz system uses a special singe-phase network connected to single-phase power plants. The length of the electrified German railway is 19857 km [25]. In the Alp countries, the system is connected to three-phase power plants of 50Hz, through a phase and frequency converter. The topology of this system is shown in *Figure 15*.

The main advantages of this system are: the constant connection from two sides, no need for neutral sections, no problems for Regenerative brakes (which will be explained in Point 3.2.3.3.3) and the power transmission in long distances achieving a distance of 40 to 60km, for this reason, the locomotives used for this system don't need braking resistors.
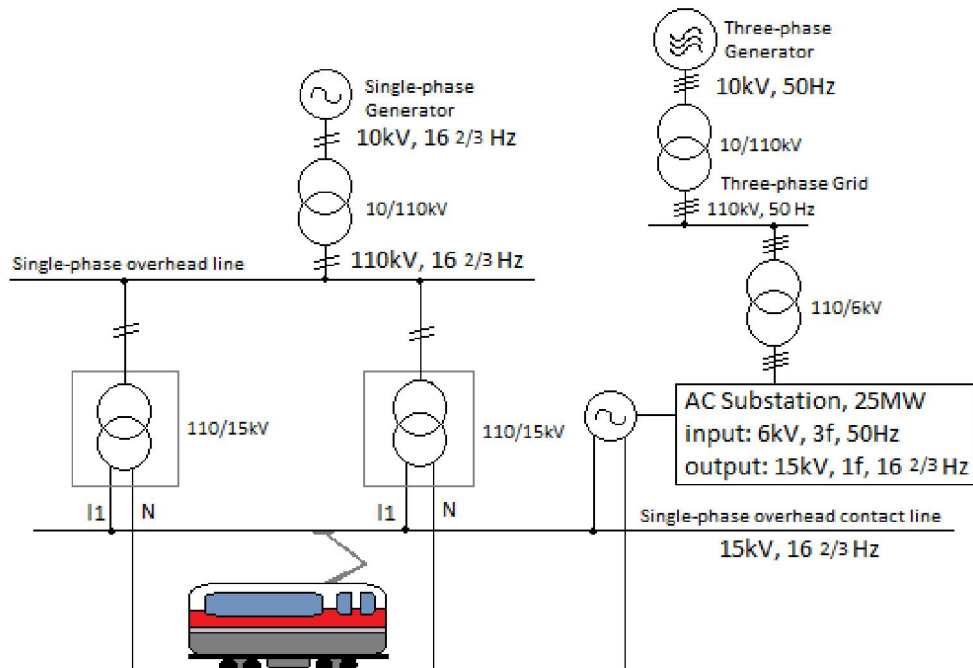
Figure 15 - Simplified diagram of an AC System for the supply of a 15kV 16 2/3 Hz Railway

(Source: Authors own work)

3.2.1.2.2   25kV 50Hz

The main reason for the existence of this system is quite simple: To use the prevalent network with its current power plants and transmission. The cause for its development was, back in the 60's, the appearance of the semiconductor rectifier, which made possible of having locomotives composed of single-phase transformers, bridge rectifiers, and DC traction motors. It was considered practical to apply in countries with no electrified railway history, for example, Bulgaria, Romania, Poland, etc. Since then, it has been adopted as the second type of system in many countries, working in parallel to the 3kV DC in Russia, Ukraine, Czech Republic and Slovakia, also to the 1,5kV of France. Even though contact points are problematic and the need of development of Multi-system units is a disadvantage, this system has a very promising potential.

The first disadvantage that came up at the beginning of the implement of this system was the asymmetric load caused by the single-phase connection; one of the solutions to this problem was to rotate the phases with particular connections of transformers in the AC substations as is shown in *Figure 16* and *Figure 17.*

19
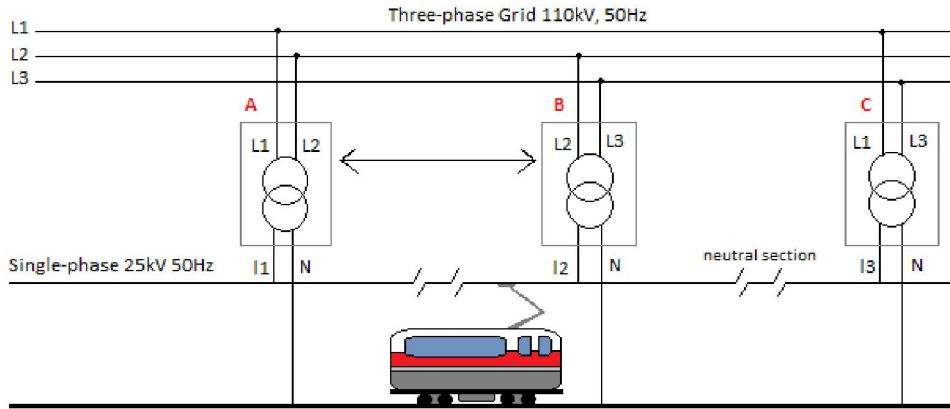
Figure 16 - Simplified diagram of an AC System for the supply of a 25kV Railway. T connection of Transformers

(Source: Authors own work)
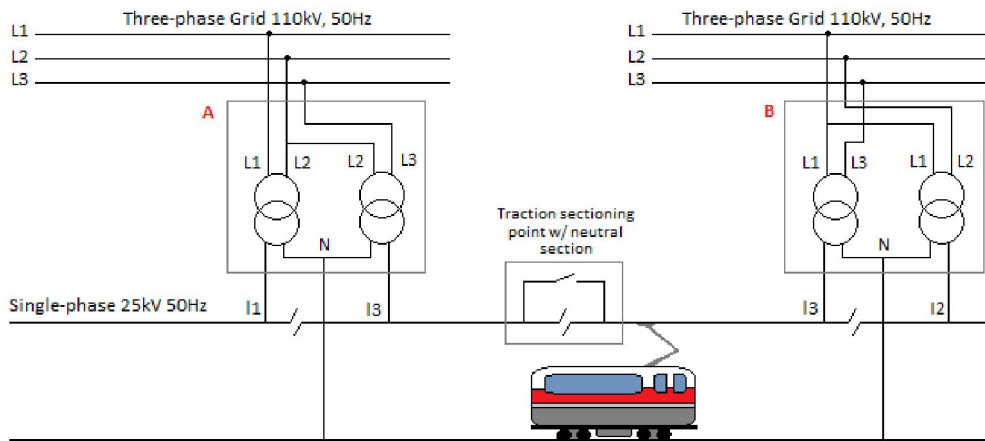
Figure 17 - Simplified diagram of an AC System for the supply of a 25kV Railway. V connection of Transformers

(Source: Authors own work)

The second problem was that the existing vehicles had a really bad power factor (cos φ). And for this reason, they were absorbing active and reactive power from the grid.

The third problem was that the existing vehicles didn't have a sinusoidal current wave, and for this reason high harmonics burdens the grid with deformed power.

The solution for the second and third problem is the application of Static Compensator stations to increase the reliability of the grid and the application on 4QR (as it was shown in Point 3.1.2.4) in vehicles to get the ideal power factor (cos φ = 1).

3.2.1.2.3   2x25kV 50Hz

This system was developed to increase the capability of the OCL, since the requirements for trains demanding higher power, a power depending enormously on the level of voltage and the reduction of the impedance of the catenary. That's how 2x25kV, 50Hz system appeared.

There are two important types of connection; the first one is the Booster Transformer Feeding system (BT) which is shown in *Figure 18* and the second one, is called Autotransformer Feeding System (AT) which is shown in *Figure 19*.
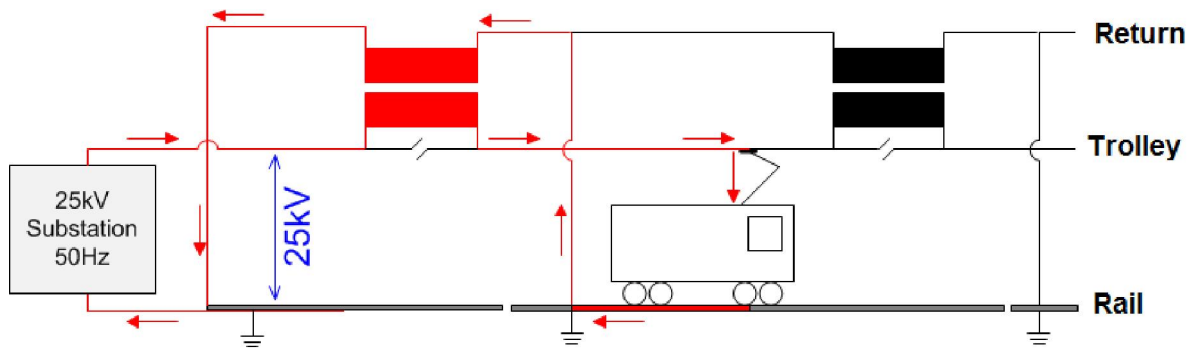
Figure 18 - Booster Transformer (BT) Feeding System 2x25kV 50Hz

(Source: Authors own work)

In comparison with the system of 25kV 50Hz, the 2x25kV 50Hz uses only one segment of the rail from point A to point B as is shown in *Figure 19* The pantograph is connected to one of the contact wires with 25kV which gives the energy to the train at the exact point of connection (in the segment where the train goes through). The second wire, the negative phase feeder, has a voltage of 25kV as well, which is shifted about 180° from the positive one.
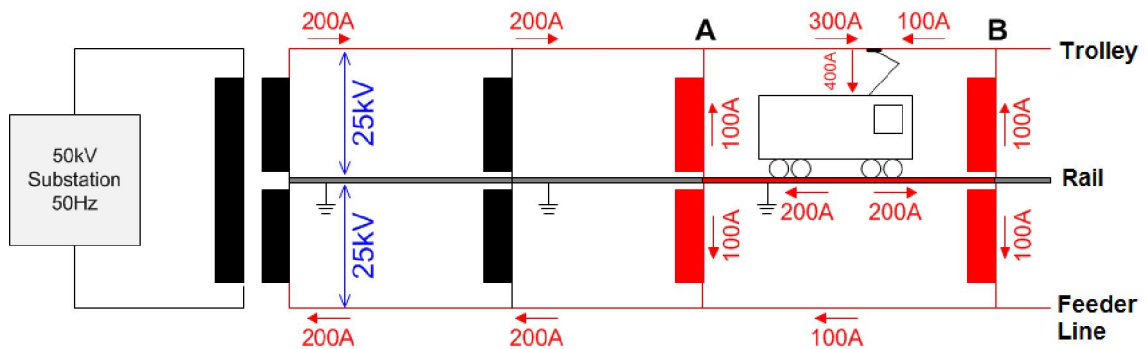
Figure 19 – Autotransformer (AT) Feeding System 2x25kV 50Hz

(Source: Authors own work)

One of the many advantages of this system is the decrease of voltage drops in the OCL caused by the reduction of the level of current, this means, lower power losses, which means saving more energy, also the attenuation of the intensity of the electric and magnetic field surrounding the OCL.

Another very important advantage is that the train is fed with current at a concrete point between two ATs, in segments where no train passes through is no consumption of energy, which limits the influence in terms of EMC and the corrosive effects on underground structures. The return conductor is only one segment of rail between these two ATs.

In comparison with Boost Transformer' system (BT), the AT has a lower number of auxiliary transformers. The distance between this transformers is about 7km longer than in the case of BT (only 3km in BT against 10km in AT).

The distance between substations can be longer; this will be proved in further Chapter 5.

Between the disadvantages of the AT system for 2x25kV 50Hz are, for example, higher number of conductors in the OCL, the substations have a more complex connection and uses a bigger amount of switching devices, the implement of AT or BT represent losses in the distribution system, which is a disadvantage for the power supply.

There is also a higher risk of short circuits because of the implementation of the higher voltage level.

3.2.2 Mechanics of the Catenaries

3.2.2.1 *Single Contact System*

In this system, the wire is suspended in a certain height and bent with a parabolic shape as is shown in *Figure 20*. It is used for vehicles which function in a low velocity, about 50 – 60 km/h, usually trams. The effort of the wire to stretch takes higher force and thus big stress on the wire.

3.2.2.2 *Simple Catenary*

The supporting cable is bent, almost in a parabolic shape as is shown in *Figure 21*, similar to the arc of a metal bridge. The contact wire is almost flat.
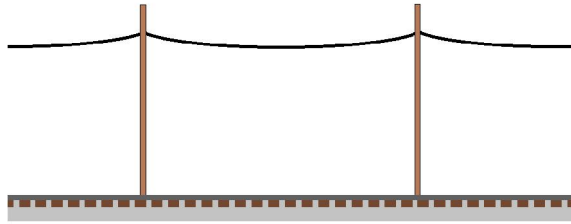
Figure 20 - Single contact system

(Source: Authors own work)
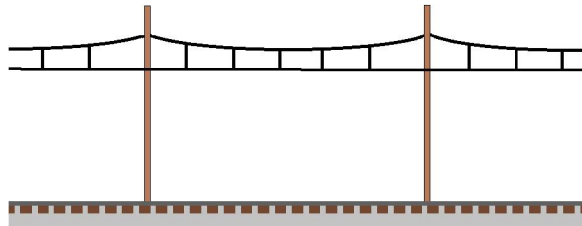
Figure 21 - Simple Catenary

(Source: Authors own work)

3.2.2.3 *Tensioning of the contact wire*

The influence of the variation of temperatures as is shown in *Figure 22*, causes a dilatation or contraction of the wire, making it too tight during winter or too saggy in summer. These phenomena can be explained from Equation (10), where L_0 is the initial distance between two ropes, α is the linear expansion coefficient, T is the surrounding temperature and L is the resulting length of the wire *[m, -, °K, m]*.

$$L = L_0(1 + \alpha\, T) \tag{10}$$
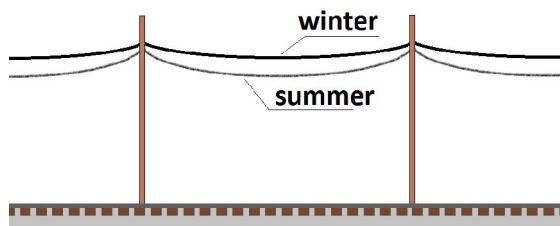
Figure 22 - Not Compensated Wire

(Source: Authors own work)

23
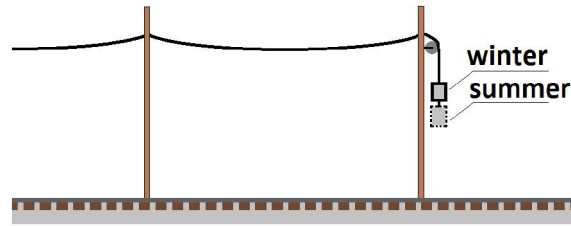
Figure 23 - Compensated Wire

(Source: Authors own work)

For medium and High-Speeds the wires are tensioned by weights or by hydraulic tensioners, it is called "constant tension" or "auto-tensioning" making it independent of the present temperature. The tenseness and the bend don't change.

3.2.2.4 *The ideal contact wire*

The ideal state of contact wires is to keep straight, to be elastic and to stay without firm points, for this we have a completely tensioned line with extra ropes near the ropes as is shown in *Figure 24*.
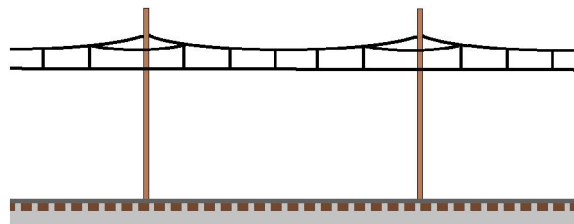
Figure 24 - Ideal Contact System

(Source: Authors own work)

3.2.2.5 *Operation Effects in the OCL*

In the progress of the railway technology during time, there were many aspects to be considered and were solved:

- The **Wear out** suffered by the contact wire caused by the connection of the pantograph to the catenary. The solution for this issue was the change the material on the pallet, from metal contacts to nonall-metallic contact, now, carbon is used.

- The **Atmospheric pressure discharges** were ensured with protection devices such as Lightning arresters.

- To prevent the **effects of Winds**, the pantographs were designed wider.

- For **freezing** cases, the wire is heated with the current flowing through it.

3.2.3 Behavior of the Voltage in the Catenaries

The current passing through the catenary not only induces power losses ΔP but also a voltages drop ΔU in the system. The effects of the voltage drops in the catenary will be explained in further Chapter 5. The behavior of the voltage drops according to the way of supply is explained in the next point 3.2.3.1.

For this reason, the voltage in the OCL is not constant, it depends on the load, for this reason in DC systems, was established a tolerance about $0,66\ U_n < U < 1,2\ U_n$ and $0,76\ U_n < U < 1,1\ U_n$ for AC, these values are described in *Table 1*.

Electrification system	Voltage [kV]				
	Min. non-permanent	Min. permanent	Nominal	Max. permanent	Max. non-permanent
1500 V DC	1	1	1,5	1,8	1,95
3kV DC	2	2	3	3,6	3,9
15kV AC 16 $^2/_3$ Hz	11	12	15	17,25	18
25kV AC 50 Hz	17,5	19	25	27,5	29

Table 1 - Different types of Electrification Systems for Rails in Europe and their Tolerances - EN 50163: Railway applications. Supply voltages of Traction Systems

3.2.3.1 *Ways of supply and their voltage drops*
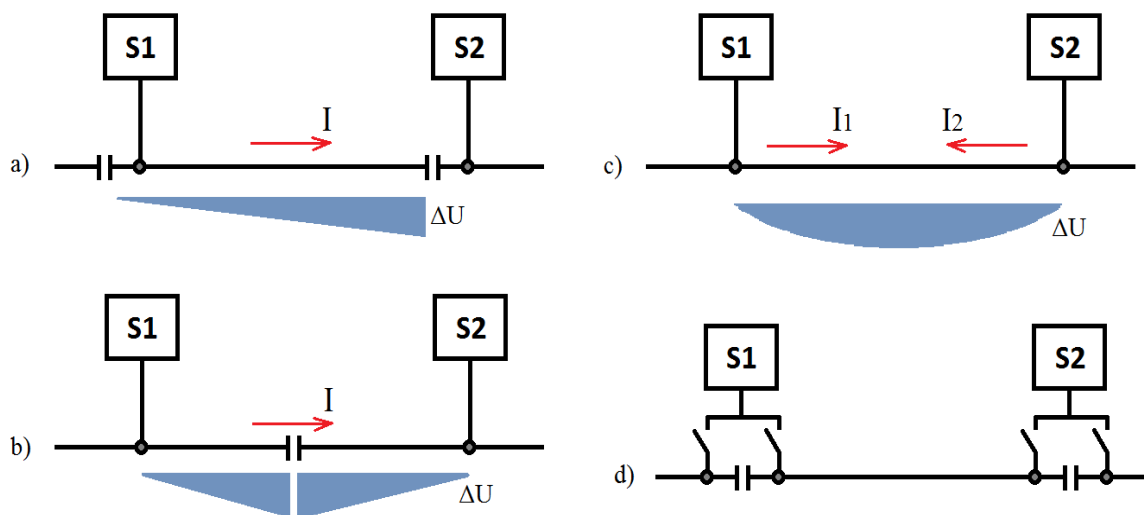
Figure 25 - Ways of supply a) One side to the end of the section, b) One side to the middle of the section, c) Both sides without separation, d) Both sides separated in the place of supply

(Source: Authors own work)

In *Figure 25* a) the voltage drops starts at the substation S1, the current flows in the direction to S2 until the neutral point. The maximum voltage drop is described in Equation (11) and reaches its value at the end of the section.

$$\Delta U_{max} = R \cdot I = r \cdot L \cdot I \qquad (11)$$

The voltage drop represented in *Figure 25* b) in comparison with a), reaches its maximum value in the middle of the section. Its value can be calculated dividing the distance by 2, as is shown in Equation (12).

$$\Delta U_{max} = r \cdot \frac{L}{2} \cdot I \qquad (12)$$

The advantages of these two first options are the easy dissipation of short circuits that might occur in the OCL, and when it happens, these failures don't have an impact on the whole system.

The disadvantages caused by the implementation of neutral sectioning are for example the need to disconnect the pantograph from the catenary to prevent the damage of the vehicle or the pantograph itself. Also, when passing through the neutral section, there is a risk of arc impact, this can be solved turning off the consumption of current without disconnecting the pantograph from the catenary.

In *Figure 25* c) there is no separation between the two stations. This brings one disadvantage: it is harder to disconnect short circuits. Its behavior can be calculated with Equation (13).

$$\Delta U_{max} = r \cdot \frac{L}{2} \cdot \frac{I}{2} \qquad (13)$$

In the last point in *Figure 25*, point d) the substations S1 and S2 are constantly connected in its normal state.

The main advantages of the last two ways of supply, the c) and d), are, mainly because they are not divided into sections, the decreasing of power losses in the OCL, also, no neutral section problems. The input voltage has less variation (collision of voltage) and in the line where a vehicle brakes there are others who accelerate, this brings us a higher probability for RB.

3.2.3.2 *Trouble caused by the discontinuous electric supply*

The disconnection of the pantograph from the contact wire or the switching off of the main circuit breaker of the vehicle can cause the interruption of the traction power, the interruption of the RB and automatically this current goes to the breaking resistances if, and only, if the vehicle is equipped with them; also, the cut-off of auxiliary devices, such as compressors, air conditioning and heating devices, ventilators, etc. The unplug of batteries and the wear out of protecting devices as well. For all these reasons, the HS vehicles are the most problematic. Because of its speed, the train passes through the neutral sectioning without enough time for switching off the main circuit breaker or for the contraction of the pantograph in order to disconnect.

3.2.3.3 *Regenerative Braking in DC and AC systems*

The RB is an excellent way to save energy since the traction motor starts to function as a generator while braking. In the case of the metro, trams, and S-Trains, it is possible to recover half of the consumed energy but the distribution companies are not interested in buying back this "extra" energy. Because of that, this energy can be used immediately by other trains traveling in the same railway or it can be storage in batteries

3.2.3.3.1 RB in 3kV DC

The rectifiers used in this type of substations are basically composed of diode-type of converters, this makes no possible for the current consumed for the vehicle to return to the grid's distributor. For this reason, the dynamic braking is providing energy to the system, and this energy can be taken as a benefit in the DC supply for other trains to speed up. The presence in a certain distance of a train (or more trains) who is demanding this energy is the basic condition for the successful function of the RB. In order for the current to flow from the braking train to the train which needs this energy, it is necessary to define an electric potential difference, which is given by the voltage drop in the catenary.

The highest RB voltage gives us the possibility to find its consumption even in long distances, for this reason, the bonding for voltages is elevated 1,2 times more of the nominal voltage, for example, when there is a nominal voltage about $U_n = 3600V$ increasing it to 20% more means $1,2U_n = 3900V$ in a period of time of 5 minutes. In the case where there are no other trains demanding for energy from the RB, this energy dissipates through the braking resistances.

3.2.3.3.2   RB in 25kV 50Hz

Theoretically possible, but, it is a quite problematic system. For this to be possible, the vehicle should not be equipped with diode rectifiers but with 4QR. In terms of infrastructure, there are very high voltage drops and the tolerance is not as wider as in the DC system, there is a high risk of saturation of the transformers. Also, the sections are shorter and the flow of current is discontinuous. Another technical concern is the possibility of the flow of energy from the substation to the grid, for this, the AC substations are equipped with "Power Relay" which activates with the presence of negative active power and immediately turns the substation off. There is a big lack of interest in economic and technical terms, is the fact that it can provoke a serious unbalance in the system, caused by the high probability of power collision due to short circuits, this brings serious consequences in the reliability of the system, which are supposed to be avoided.

3.2.3.3.3   RB in 15kV 16 ⅔ Hz

The RB in this system is used without any problem and is considered very successful. The trains are normally equipped with dynamic brakes and 4QR, which makes possible the energy to flow in both ways. Transformers are also prepared to let the current flow in both directions. The catenary is connected from two sides and it goes uninterrupted through all the OCL without any sectioning point. When the energy is not used in one point of the railway it can be used somewhere else. The probability of RB is really high and for this reason, many of the trains which work in this system don't need to be equipped with braking resistances, and if they do, they are smaller.

3.2.3.4 *Voltage Reactive Power Compensation and the Consequences of High Harmonics*

One of the greatest problems when dealing with single-phase power supply for trains, in the case of 25kV and 2x25kV is the unbalance of the system. To solve this issue, it is necessary to install the so called "Compensators" or "Balancers".

The FACTS are electronic-based devices able to control the transmission of AC systems to enhance power transfer capability. The fast regulation of voltage under any condition, the increment of power of the AC lines, providing balance of the active and reactive power of the system, to control the damping of the oscillations, to increase the stability over long distances are the tasks of the FACTS devices. One of them is the well-known SVC (Static VAr Compensator) described in *Figure 26*. The type of topology to implement (TCR, TSC or Filter) depends on the requirements and the size of the system.
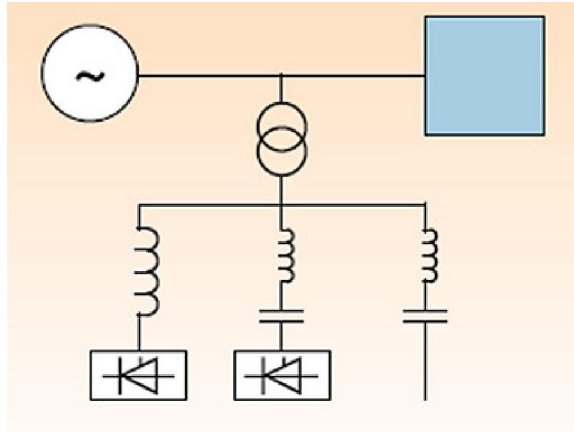
Figure 26 - Topology of a SVC coupled to the network via a high voltage transformer **[26]**

Another great device that can help to stabilize the system, it is made by the company SIEMENS, the Sitras RAB plus and its connection to the Power Substation is shown in *Figure 27*. The Sitras RAB plus measures the load current of the OCL for Railways, it supplies with reactive current to the net, which gives a resulting symmetrical load. Also accomplish the function of compensation of reactive power to the OCL. This device can be connected to the High-Voltage grid or directly to the 25kV BUS-bar.
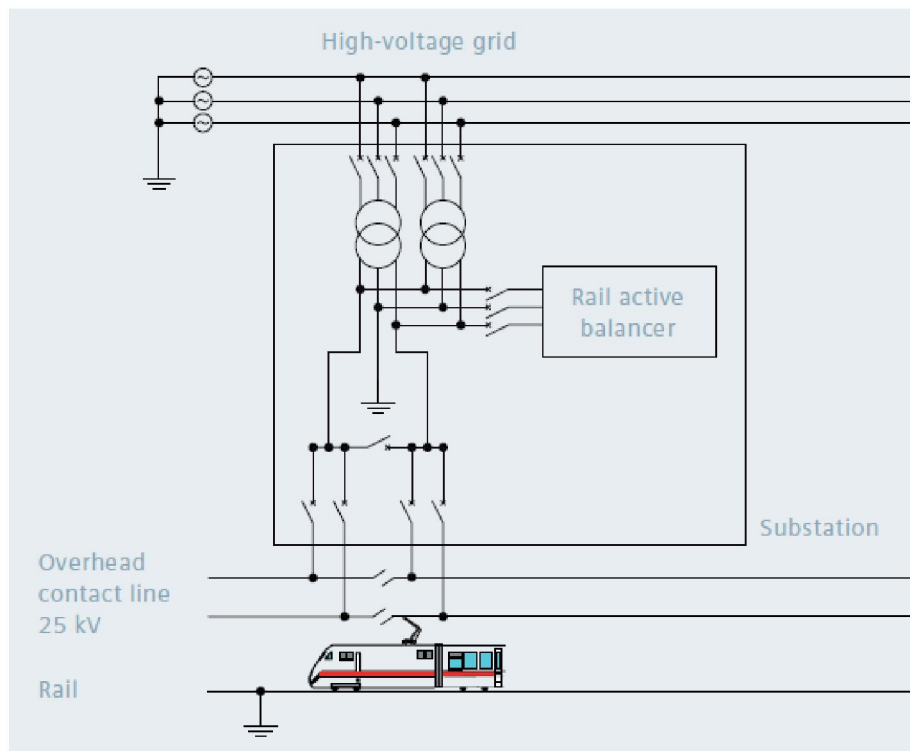
Figure 27 - System integration of rail active balancer Sitras RAB plus **[27]**

4 Practical Part

4.1 Parameters of the Rolling Stock

The most important parameter of the Rolling Stock is its power factor, the higher it is, the better are the conditions for the supply.

According to the norm ČSN EN 50338, the total inductive power factor λ described in Equation (14) has to obey the values given in *Table I - Total inductive power factor λ of a train.*

$$\lambda = \frac{Real\ Power,\ P}{Apparent\ Power,\ S} = \cos\varphi_V \tag{14}$$

In that table is given that the power factor λ (%) for trains operating in HS TSI, with power $P \leq 6MW$ its power factor has to be $\lambda \geq 0,93$ and for trains with $P > 6MW$ must have a power factor $\lambda \geq 0,95$.

In the norm ČSN EN 50338 is also given the term of "Automatic Regulation" to facilitate a stable operation of trains in certain supply conditions or in exceptional working conditions, those trains should be equipped with automatic regulators, which adapts to the level of voltage with is currently in the pantograph, in *Figure 28* are described three working areas, the first one, labeled as "A", is the area where no traction is connected, which means in simple terms that auxiliary drives are connected to the pantograph. The area "C" is the working area for all drives, including traction and auxiliary devices. The most delicate region, the area "B" is where the current levels are exceeded. This area has to be avoided, if not, the supply collapses. This interaction between the Rolling Stock and the Supply will be shown in the graph results in Chapter 5.
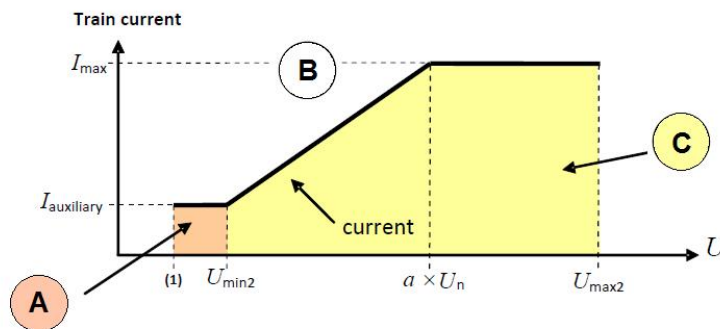
Figure 28 - Maximum train current against voltage [28]

The values for *a* according to the norm, for AC 25kV 50Hz system, is 0,9, this means that the maximum current I_{max} reaches its maximum value at the 90% of the Nominal Voltage U_n.

To restrict this current, the train must be equipped with a regulator that can choose to work in "current regime" or in "power regime".

In *Table 2*, the values used for the calculation of the behavior of the Supply system were chosen for further analysis.

Symbol	Units	Rolling Stock for DC
P_T	kW	6000
η_{PT}	%	90
P_{AUX}	kW	100
P_H	kW	433
P_C	kW	7200
U_{nV}	V	3000

Table 2 – Nominal values for Rolling Stocks in DC systems

(Source: Authors own work)

The total power of the Vehicle, which is calculated in Equation (15), is applied to both DC and AC vehicles.

$$P_C = \frac{P_T}{\eta_{PT}} \cdot 100 + P_H + P_{AUX} \tag{15}$$

In AC systems, the current absorbed by the vehicle is represented by Equation (16), the actual current absorbed by the vehicle is represented by Equation (17), and it shows its dependence on the power factor of the system.

$$I_{IN}^* = \frac{P_C}{U_{nV}} \tag{16}$$

$$I_{IN} = \frac{I_{IN}^*}{\cos\varphi_V} \tag{17}$$

In *Table 3* are the parameters used to calculate the behavior of AC machines, there are two types, the conventional AC locomotive, and the HS. There is taken to account the ideal vehicle with an ideal power factor of *cos ϕ_v = 1*, and with the lowest permitted value of power factor *cos ϕ_v = 0,95*, from the norm ČSN EN 50338.

Symbol	Units	Conventional AC Locomotive		High-Speed	
P_T	kW	6000		2x8000	
η_{PT}	%	85		85	
P_{AUX}	kW	100		100	
P_H	kW	433		800	
P_C	kW	7592		19124	
U_{nV}	V	25000		25000	
$I_{IN}{}^*$	A	304		789	
$cos\varphi_V$	-	1	0,95	1	0,95
φ_V	°	0	18	0	18
I_{IN}	A	304	320	789	830

Table 3 - Values for Rolling Stocks in AC systems

(Source: Authors own work)

4.2 Physical parameters of the Electrical Infrastructure

4.2.1 AC and DC Substations

The most important values to take to account for the both types of substations are the Nominal Values of Voltage, Current and Power of each Unit shown in Equation (18), and from that we get the Total Nominal Power is given by the Equation (19), which will be used in further calculations. Those Values are clearly seen in *Table 4*.

$$P_n = U_n I_n \tag{18}$$

$$P_{cn} = P_n N \tag{19}$$

Symbol	Units	Values DC	Values AC
U_n	kV	3,3	27,5
I_n	kA	1,5	0,50
P_n	MW	4,95	13,75
N	-	3	2
P_{cn}	MW	14,85	55

Table 4 - Values for Substations for AC and DC Systems Supply

(Source: Authors own work)

4.2.2 The Overhead Contact Line

The OCL is set by the components which are shown in *Figure 30*, in this chapter will be described the consequences of choosing certain sizes, shapes and materials for conductors.
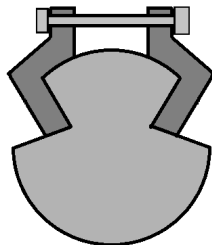
Figure 29 - Cross Section of the Trolley Wire

(Source: Authors own work)
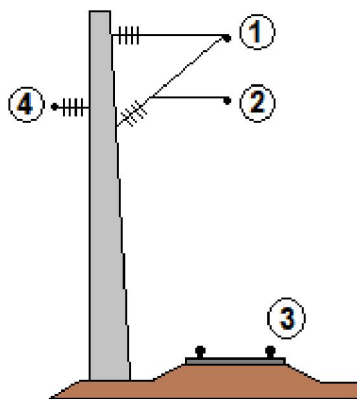
Figure 30 - Arrangement of the Mast 1) The Catenary Wire 2) The Trolley Wire, 3) The Rail, 4) The Feeder Line

(Source: Authors own work)

In DC systems, the cross section area of the Trolley Wire is usually 150 mm^2, and 120 mm^2 for the Catenary Wire (CW). Both Wires are copper made material. In the case of the Feeding Line (FL), for the diameter of 120 mm^2, it was chosen copper as well. For the diameters of 240 and 480 mm^2 the material used is Aluminium.

In *Table 5*, are the values for materials and diameters used in DC and AC Supplies, in the DC the calculations are made in 4 possible cases, first without FL, then with FL of 120, 240 and 480 mm^2, respectively. In the AC case is compared the case without FL and with an FL of 240mm^2.

Symbol	Units	DC				AC	
		No FL	FL 120	FL 240	FL 480	No FL	FL 240
S_{FL}	mm^2	-	120	240	480	-	240
p_{oFL}	%	-	0	0	0	-	0
ρ_{FL}	Ωmm^2/m	-	0,018	0,028	0,028	-	0,028
S_{CW}	mm^2	120	120	120	120	70	120
p_{oCW}	%	0	0	0	0	0	0
ρ_{CW}	Ωmm^2/m	0,018	0,018	0,018	0,018	0,025	0,025
S_{TW}	mm^2	150	150	150	150	100	120
p_{oTW}	%	10	10	10	10	10	10
ρ_{TW}	Ωmm^2/m	0,018	0,018	0,018	0,018	0,024	0,024
Δt	K	60	60	60	60	40	40
α	K^{-1}	0,004	0,004	0,004	0,004	0,004	0,004

Table 5 - Values for the parts of OCL

(Source: Authors own work)

In the other hand, this alloy, comparing to clean copper wire, has worse resistive properties. To compensate this difference, the diameter is enlarged (that's why is the 100mm^2 and the 120mm^2 implemented).

The shape of the TW can be seen in *Figure 29*. The FL in AC systems is usually made from Bronze.

In this point, the GR of the Trolley Wire, the Catenary Wire, and the Feeding Line are calculated with Equation (20). Where *x = TW, CW or FL*.

$$\nabla R_X = \frac{\frac{\rho_x(1 + \alpha\Delta t)}{S_x}}{(100 - p_o)/100} \tag{20}$$

To calculate the Total Gradient Resistance of the Overhead Line, the Equation (21) was used. The results are in *Table 6*.

$$\nabla R_{OCL} = \frac{1}{\frac{1}{\nabla R_{TW}} + \frac{1}{\nabla R_{CW}} + \frac{1}{\nabla R_{FL}}} \tag{21}$$

Resulting Values							
Symbol	**Units**	**DC**				**AC**	
		No FL	**FL 120**	**FL 240**	**FL 480**	**No FL**	**FL 240**
∇R_{TW}	mΩ/km	165	165	165	165	208	231
∇R_{CW}	mΩ/km	186	186	186	186	371	217
∇R_{FL}	mΩ/km	-	186	145	72	-	135
∇R_{OCL}	**mΩ/km**	**88**	**60**	**55**	**40**	**133**	**61**

Table 6 – Total Resistance Gradient of the OCL

(Source: Authors own work)

These resulting values are then used for further calculations.

4.2.3 The Rails

The behavior of current trough a conductor, when we talk about DC current, flows through the whole rail's area as is shown in *Figure 31* on the left.

In the case of AC, the current flow distribution takes place, most of it, between the surface and the skin depth *x* as is shown in the right side of *Figure 31*, this effect is caused by the electrical and magnetic properties of the conductor and the frequency of the current.
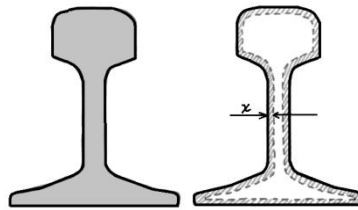
Figure 31 - Profile of rails exposed to DC (left) and AC (right) currents

(Source: Authors own work)

To avoid any consequences caused by the return current, in terms of reliability, the resistance of the return conductor has to be taken into account. One of the biggest disadvantages of the DC system is the effect of stray voltages, for this reason, is established the compliance of a really high resistance between the rail and ground.

This stray voltage not only is dangerous for living things which can be exposed to electrocution, but it also causes a tremendous damage to the metal structures surrounding the train line, wearing out the metal surfaces. This reaction is commonly known as "Galvanic Corrosion", destabilizing civil engineering structures as bridges, reinforced concrete, tubes, etc.
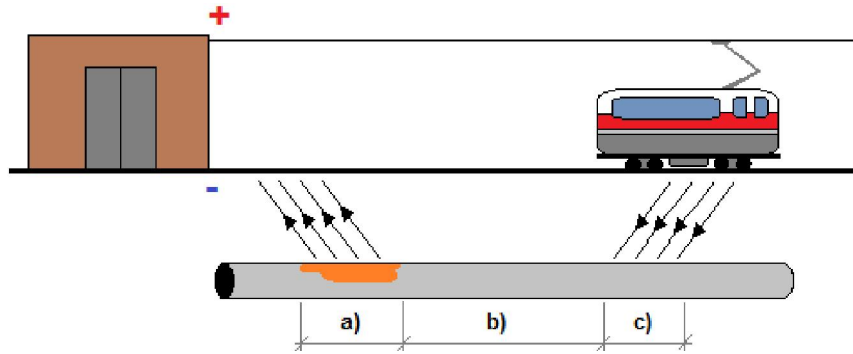
Figure 32 - Corrosion caused by the DC system in an Urban Transportation System, a) Anodic area, b)
Neutral Area c) Catodic Area
(Source: Authors own work)

The detachment of metal occurs in what is called "Anodic area" a) and it is shown in *Figure 32*, this phenomenon can be explained thanks to Faraday's law, which establishes that the amount of detached metal *Δm* depends on the value of DC current *I* and the time *t* of its exposition as is shown in Equation (22), where *C* is a constant.

$$M = C \int i \, dt \ \rightarrow \ \Delta m = \frac{I \cdot t}{C} \tag{22}$$

Just to have an idea of the impact caused by the DC stray current of the system, a current of 1A can disband 7kgs of metal if it flows uninterruptedly for one year [29].

The first solution for this problem is the complete disconnection of the grounding of the DC Substation, the second solution is to isolate the rails, and the third are the implementation of different types of protections such as the sacrificial anode, the cathode protection, etc.

At this point is necessary to calculate the Gradient Resistance of the rail, for which is used the Equation (20), the parameters used and the resulting value are in *Table 7*.

Symbol	Units	Values DC
∇m	kg/m	60
ρ_m	kg/dm^3	7,8
S_K	mm^2	7692
p_{oK}	%	0
ρ_K	Ωmm^2/m	0,28
Δt	K	20
α	K^{-1}	0,004
∇R_{DC}	mΩ/km	20

Table 7 - Values of parameters of the Rails for DC
(Source: Authors own work)

In the case of AC currents, stray voltages are so insignificant, and the damage is so small that they can be neglected. Even though its damages can be ignored, the behavior of AC currents in rail has to be also taken to account for further calculations.

Symbol	Units	Values AC
∇m	kg/m	60
ρ_m	kg/dm^3	7,8
S_k	mm^2	7692
p_{oK}	%	0
ρ_K	Ωmm^2/m	0,28
Δt	K	20
α	K^{-1}	0,004
∇R_B	mΩ/km	20
f	Hz	50
μ	H/m	1,26 x10^{-6}
μ_r	-	500
x	mm	1,68
p	mm	400
d_v	mm^2	674
ΔR_K	%	1142
∇R_{AC}	mΩ/km	224

Table 8 - Values of parameters of the Rails for AC
(Source: Authors own work)

For this, the Equation (23) calculates the skin depth, from which the conductive area is calculated in Equation (24) and is used to calculate the increase of resistivity in Equation (25).

$$x = \sqrt{\frac{\rho \cdot 2}{2\pi f \mu_0 \mu_r}} \tag{23}$$

$$d_v = x \cdot p \tag{24}$$

$$\Delta R_K = \frac{S_k}{d_v} \cdot 100 \tag{25}$$

The resulting Gradient Resistance of the rail, in AC system, is calculated with Equation (26), the numerical results are in *Table 8*.

$$\nabla R_{AC} = \Delta R_K \cdot \nabla R \tag{26}$$

4.2.4 The Ground

Because of Stray Voltages in DC systems, the rails have to be perfectly isolated from the ground, avoiding as much as possible the leakage of current.

To avoid the consequences of corrosion it is necessary to make some measurements. The most commonly are the measurement of the resistivity of the soil, the intensity and the current density of the ground. From these magnitudes we can confirm the level of aggressiveness of the land, in terms of electrochemical corrosion and from this are calculated the dimensions of the devices to apply.

Level	Aggressiveness of the Ground	ρ (Ωm)
I	Slightly corrosive	> 100
II	Moderately corrosive	50 to 100
III	Corrosive	23 to 50
IV	Severe	< 23

Table 9 - Classification of ground aggressiveness according to its resistivity

There are also other factors which have to be taken into account are, for example, the humidity of the soil, its salt content, and its temperature.

For the calculations on this thesis, the value chosen for the Gradient Resistivity of the Ground was of $\nabla R_G = 200 \ m\Omega/km$

4.2.5 The Return Wire

Since the Return in DC system is through the Rails, in this point the return wires in AC systems will be discussed.

To obtain the Total Gradient Resistance in Equation (28) is necessary to calculate the Return Line GR, with Equation (27), after obtaining the value of GR of the Rails Equation (26) and the Ground in AC system in previous points 4.2.3 and 4.2.4 of this chapter.

$$\nabla R_{RL} = \frac{1}{\frac{1}{\nabla R_{AC}} + \frac{1}{\nabla R_G}} \tag{27}$$

$$\nabla R_{TR} = \nabla R_{OCL} + \nabla R_{RL} \tag{28}$$

To find the Total GR resistance of the system, the radius of the wire had to be calculated (Equation (29)), also the Gradient Inductance, Reactance as are shown in Equations (30) and (31).

$$r = \sqrt{\frac{S_{TW}}{\pi}} \tag{29}$$

The height to calculate the Gradient Inductance, for the case without Feeder Line, is about 6m, which represents the distance of the Trolley Wire to the Rail, in the case with Feeder Line, the height chosen is about 1m, and it represents the distance between the Trolley wire and the Return Line.

$$\nabla L = 0,46 \, log\left(\frac{H}{r}\right) \tag{30}$$

$$\nabla X = 2\pi f \cdot \nabla L \tag{31}$$

The impedance in Equation (32) is then used to obtain the power factor and the phase angle of the whole Overhead Line, in the Equations (33) and (34), respectively.

$$\nabla Z = \sqrt{\nabla R_{TR}{}^2 + \nabla X^2} \tag{32}$$

$$cos \, \varphi_{OCL} = \frac{\nabla R_{TR}}{\nabla Z} \tag{33}$$

$$\varphi_{OCL} = arccos\left(cos \, \varphi_{OCL} \cdot \frac{180}{\pi}\right) \tag{34}$$

The results for the two variants, with and without Feeder Line are in *Table 10*. From the results can be concluded that the Total GR of the OCL, decreases almost in a 50% with the implementation of the Feeder Line in a distance *l* twice as longer.

Symbol	Units	No FL	FL 240 Cu
∇R_{RL}	mΩ/km	106	55
r	mm	5,6	6,2
H	m	6	1
∇L	mH/m	1,44	1,07
∇X	mΩ/km	453	335
∇Z	mΩ/km	512	335
$cos \, \varphi_{OCL}$	-	0,47	0,33
φ_{OCL}	°	62	74
l	km	22	44
n_{IN}	-	1	1
∇R_{TR}	mΩ/km	239	117

Table 10 - Values for the Return Wire in AC system
(Source: Authors own work)

In the case of DC systems, the total Gradient Resistance is the sum of the GR in the Trolley Wire and the GR in the Rail as is shown in Equation (35). The values for ∇R_{OCL} are in *Table 6* and ∇R_{DC} in *Table 7*.

$$\nabla R_{TR} = \nabla R_{OCL} + \nabla R_{DC} \tag{35}$$

4.3 Voltage and Power Resulting Parameters of the Power Supply System

In order to visualize the behavior of the Voltage on the power supply, the effect of the Rolling Stock traveling from one Substation to another, it is necessary to calculate the Voltage drops and the Power in every kilometer of the section. From this calculations are obtain the results in further chapters 5.2 and 5.3 for DC and AC Systems respectively, coinciding with the theory which was provided before in chapter 3.2.3.1, specifically in *Figure 25*.

4.3.1 On DC System

In the case of DC system, the calculations were made at a distance of 22 km; the way of supply is from two sides as is *Figure 25* in c) *Both sides without separation*

To start the calculation, it was necessary to have in hand the parameters of the Rolling Stock, the GR of each component of the Overhead Line: the Trolley wire, the Catenary Wire the Feeder line (if it is implemented) the Ground, the Rail and the Return Wire.

In Equation (36) is calculated the current taken by the Rolling Stock from one side of the Supply,

$$I_{1s} = \frac{I_{IN}}{2} \tag{36}$$

From this value is calculated the Voltage Drop at the middle of the Section in Equation (37), also taking to account the Total GR of the power Supply ∇R_{TR}.

$$\Delta U_{\frac{l}{2}} = 2 \cdot l \cdot I_{1s} \cdot \nabla R_{TR} \tag{37}$$

Then, the calculation of the Input voltage with Load, obtained from the input voltage without load, which is usually 3500V in this thesis, plus, the single side current times the internal resistance of the Substation, explained in Equation (38). The voltage at the middle of Section is given by Equation (39).

$$U_{inL} = U_{inNL} + R_{iS}I_{1s} \tag{38}$$

$$U_{l/2} = U_{inNL} + \Delta U_{l/2} + \frac{R_{iS}I_{IN}}{2} \tag{39}$$

The rest of the voltage drops are the Voltage drops occurring in the OCL in Equation (40), and the one in the Rail, shown in Equation (41).

$$\Delta U_{OL} = 2 \cdot l \cdot I_{1s} \cdot \nabla R_{OCL} \tag{40}$$

$$\Delta U_R = 2 \cdot l \cdot I_{1s} \cdot \nabla R_{RL} \tag{41}$$

The other important value, to examine the behavior of a system, is to have a look on the power in the overhead line, for example, the power in the middle of section (42) and the most important value to monitor is the Power Loss in the Supply, the maximum value is given by the equation (43), showing its maximum value in the middle of the Section. From this is also important to observe the Average Power of the Power Supply in (44).

$$P_{\frac{l}{2}} = U_{nIN} \cdot I_{IN} \tag{42}$$

$$\Delta P_{\frac{l}{2}} = \Delta U_{\frac{l}{2}ACT} \cdot I_{IN} \tag{43}$$

$$P_{nIN} = P_{\frac{l}{2}} + \Delta P_{\frac{l}{2}} I_{IN} \tag{44}$$

In order to evaluate the system, it is necessary to evaluate the efficiency of the Power Supply given by Equation (45).

$$\eta_{l/2} = \frac{P_{\frac{l}{2}}}{P_{nIN}} \cdot 100 \tag{45}$$

$$p_{l/2} = 100 - \eta_{l/2} \tag{46}$$

From the previous calculations and the collection of data, it was possible to show in *Table 11*, there are described the values for the beginning of the supply and the middle of the sections.

From there we can realize how the implementation of FL of different diameters and the regulation of the Rolling Stocks have an impact on the efficiency of the whole system.

Symbol	No FL			120 FL			240 FL			480 FL		
	I	P	AR	I	P	AR	I	P	AR	I	P	AR
$U_{l/2}$	2013	#	2427	2383	#	2530	2449	#	2553	2646	2457	2633
U_{nIN}	3000	#	3500	3000	#	3500	3000	#	3500	3000	3500	3500
U_{inL}	3428	#	3448	3428	#	3437	3428	#	3435	3428	3412	3427
U_{inNL}	3500	#	3500	3500	#	3500	3500	#	3500	3500	3500	3500
I_{1s}	1200	#	866	1200	#	1042	1200	#	1081	1200	1465	1218
ΔU_{OCL}	1155	#	834	786	#	682	720	#	649	523	638	531
ΔU_R	259	#	187	259	#	225	259	#	234	259	317	263
$\Delta U_{\frac{l}{2}}$	1415	#	1021	1045	#	907	979	#	882	782	955	794
$P_{\frac{l}{2}}$	4832	#	4203	5719	#	5272	5877	#	5520	6350	7200	6414
$\Delta P_{\frac{l}{2}}$	3395	#	1767	2508	#	1891	2350	#	1908	1877	2799	1935
P_{nIN}	8227	#	5970	8227	#	7163	8227	#	7427	8227	9998	8349
$\eta_{l/2}$	59	#	70	70	#	74	71	#	74	77	72	77
$p_{l/2}$	41	#	30	30	#	26	29	#	26	23	28	23

Table 11 - Behavior of Power and Voltage in DC System

(Source: Authors own work)

4.3.2 On AC System

In the case of the AC System, in comparison with the DC system, are taking the same equations, starting from the (36), ending up to (62), adding the Resistance R, the Reactance X and the Impedance Z of the system described in Equations (47), (48) and (49),

$$R_{l/2} = \frac{l/2}{2} \cdot \nabla R_{TR} \tag{47}$$

$$X_{l/2} = \frac{l/2}{2} \cdot \nabla X \tag{48}$$

$$Z_{l/2} = \frac{l/2}{2} \cdot \nabla Z \tag{49}$$

Also, the values of R, X and Z of the Power Supply taking to account the internal X_T and R_T of the Transformers in the Substations (49), (50) and (51),

$$R_{n/2} = R_T \cdot 2 + R_{l/2} \tag{50}$$

$$X_{n/2} = X_T \cdot 2 + X_{l/2} \tag{51}$$

$$Z_{n/2} = \sqrt{R_{n/2}{}^2 + X_{n/2}{}^2} \tag{52}$$

and the power factor of the power Supply (53), and the effects of the Phase angle of the Power Supply and the Voltage Drop (55)

$$cos\varphi_n = \frac{R_{n/2}}{Z_{n/2}} \tag{53}$$

$$\Delta U_{nIN} = I_{IN} \cdot Z_{n/2} \tag{54}$$

$$\varphi_{\Delta U} = \varphi_{Zn} - \varphi_V \tag{55}$$

In order to obtain the Voltage in a concrete feeding point, it is necessary to use the equation (56) and from there the Active Power of the Power Supply at that specific point is calculated with the equation (57)

$$U_{nIN} = \sqrt{U_{OUT}{}^2 - \left(\Delta U_{nIN} \cdot sin(\varphi_{\Delta U} \cdot \frac{\pi}{180°})\right)^2} - \Delta U_{nIN} \cdot cos(\varphi_{\Delta U} \cdot \frac{\pi}{180°}) \tag{56}$$

$$P_{nIN} = U_{nIN} * I_{IN} \tag{57}$$

In Equations (58), (59), (60), (61) and (62), the Average values are described, in order to compare the performance of the system with the implementation of FL –or the lack of it- and the application of constant current, constant power and Automatically regulated Rolling Stocks.

$$\Delta P_{AV} = \frac{n_{IN}}{n_{IN} + 1} \cdot \Delta P_{\frac{l}{2}} \tag{58}$$

$$P_{AV} = P_{nIN} - \Delta P_{AV} \tag{59}$$

$$\eta_{lAV} = \frac{P_{AV}}{P_{nIN}} \cdot 100 \tag{60}$$

$$p_{AV} = 100 - \eta_{lAV} \tag{61}$$

$$p_{PAV} = \frac{\Delta P_{AV}}{P_{AV}} \cdot 100 \tag{62}$$

In *Table 12* are described the resulting values calculated for the AC Systems, in the beginning of the supply and their reached maximum values in the middle of the section. In the first column are the values obtained for a distance of 22 km without feeder line, in the second

part are calculated with a distance of 44 km, in CT Infrastructure for Automatic Regulated conventional Trains and for HS, with a HS Infrastructure and with a supply of 2x25kV. The last column on the right describes the same system as the 2x25kV with *240* mm² FL but for a distance of 88 km.

Between the resulting Average values can be seen that the Power increases, but the efficiency of any of them are quite high in comparison to DC, reaching average values of efficiency η_{lAV} closer to a 100 % than in the case of DC.

Symbol	22 km	44 km				88 km
	CTI I	CTI AR	CTI HS	HSI HS	HSI HS 2x25kV	HSI HS 2x25kV
$R_{l/2}$	2,63	5,26	5,26	2,65	2,57	5,13
$X_{l/2}$	4,98	9,62	9,62	7,02	7,37	14,74
$Z_{l/2}$	5,64	10,97	10,97	7,51	7,80	15,61
$R_{n/2}$	2,83	5,46	5,36	2,75	2,67	5,23
$X_{n/2}$	5,98	10,62	10,12	7,52	7,87	15,24
$Z_{n/2}$	6,62	11,94	11,45	8,01	8,31	16,11
$cos\varphi_n$	0,43	0,46	0,47	0,34	0,32	0,32
φ_{Zn}	65	63	62	70	71	71
ΔU_{nIN}	2010	3 627	9 037	6 320	3 277	6 355
$\varphi_{\Delta U}$	65	63	62	70	71	71
U_{nIN}	26581	25 652	22 086	24 680	53 860	52 606
I_{1s}	304	304	789	789	394	394
ΔU_{OCL}	445	891	2 314	1 063	531	1 063
ΔU_R	353	707	1 836	1 030	481	963
$\Delta U_{\frac{l}{2}}$	799	1 597	4 150	2 093	1 013	2 026
$P_{\frac{l}{2}}$	8072	7 790	17 425	19 471	21 246	20 751
$\Delta P_{\frac{l}{2}}$	243	485	3 274	1 651	400	799
P_{nIN}	8314	8 275	20 699	21 122	21 646	21 550
$\eta_{l/2}$	97	94	84	92	98	96
$p_{l/2}$	3	5,86	15,82	7,82	1,85	3,71
ΔP_{AV}	121	243	1 637	826	200	400
P_{AV}	8193	8 032	19 062	20 297	21 446	21 151
η_{lAV}	99	97	92	96	99	98
p_{AV}	1	2,93	7,91	3,91	0,92	1,85
p_{PAV}	1	3,02	8,59	4,07	0,93	1,89

Table 12 - Behavior of Power and Voltage in AC System

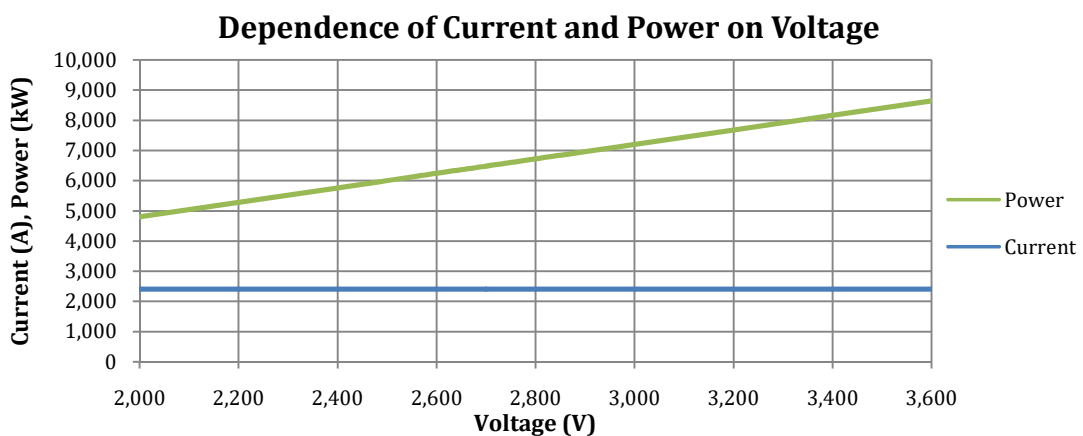*(Source: Authors own work)*

5 Results and Discussion

In this chapter are the expanded graphical results from the previous Chapter 4. There were shown the results only in a few points, here we can see the some values related to another and the behavior of the Power Supply in each kilometer of distance between two substations.

5.1 Results for the Rolling Stocks

It is necessary to differentiate the types of Rolling Stocks according to the power and current they consume and, from this, the behavior of the power supply under the influence of each of them.

5.1.1 Dependence of Current and Power on Voltage of the Rolling Stocks

The first type of Rolling Stock is the one which is absorbing a "Constant Current" from the power supply and it experiments an increasing of power while increasing the supply voltage as it is in *Figure 33*.

Figure 33 - Dependence of Current and Power on DC Voltage under Constant Current

(Source: Authors own work)

The second type of Rolling Stock is the one which is absorbing a "Constant Power" from the power supply and it experiments a variation of current as is shown in *Figure 34* while increasing the value of voltage.
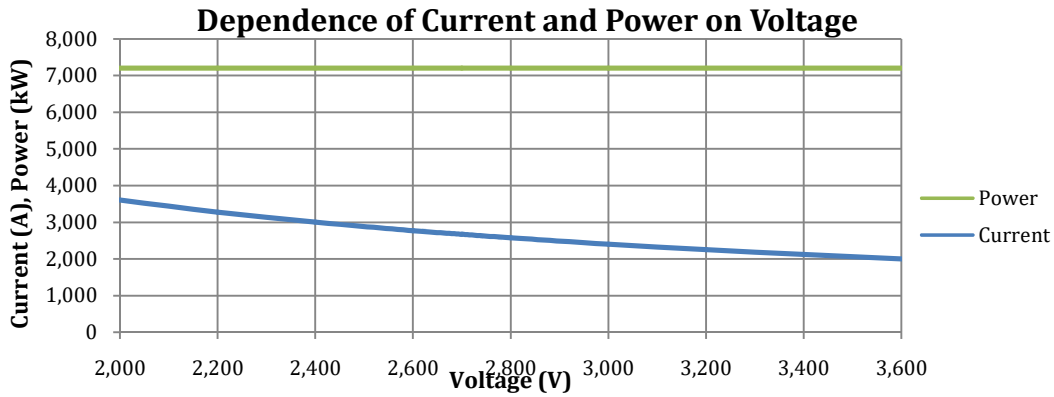
Figure 34 - Dependence of Current and Power on DC Voltage under Constant Power

(Source: Authors own work)

The third type of Rolling Stock is the "Automatic Regulated" (in obedience with the norm ČSN EN 50338) which was previously described in point 4.1 in Chapter 4. The description of the dependence is shown in *Figure 35*, where the power and current gradually increase until they reach their maximum, and then, the power behaves constantly causing a slow downturn of the current.
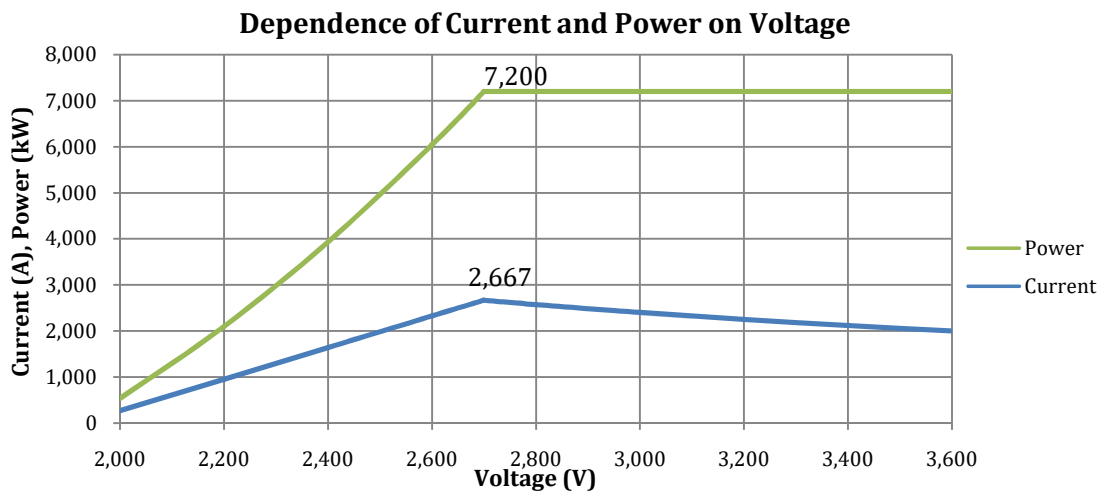

Figure 35 - Dependence of Current and Power on DC Voltage under Automatic Regulation

(Source: Authors own work)

In the case of AC systems, there were used the first type of Rolling stock described before, the "Constant Current" type and the "Automatically Regulated" one. Both of them are described in *Figure 36*.
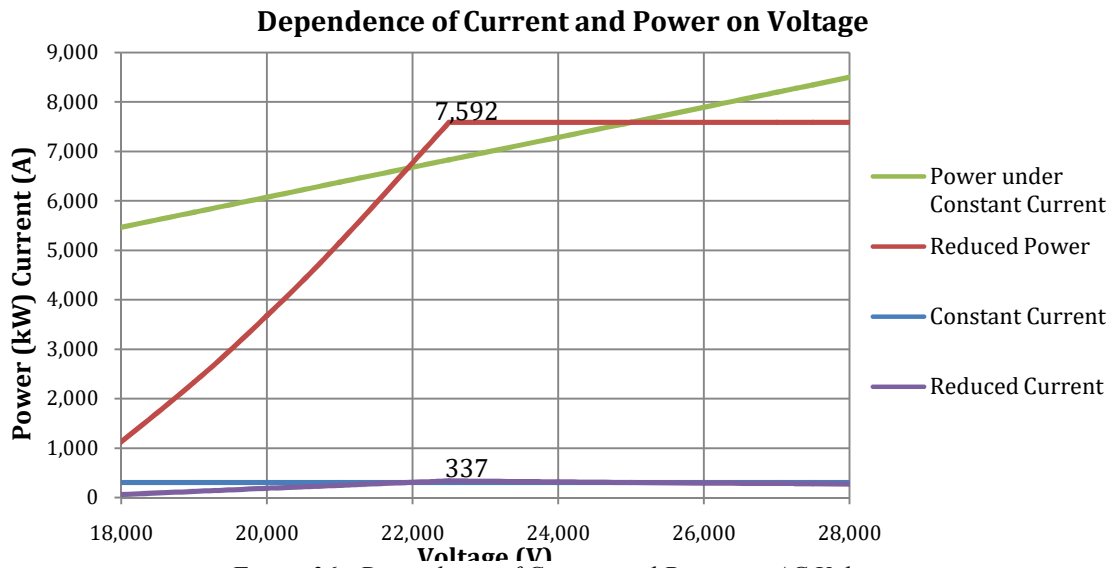
Figure 36 - Dependence of Current and Power on AC Voltage

(Source: Authors own work)

5.1.2 V-A Characteristics of the Power Supply and the Rolling Stock

When the Rolling Stocks and the Power supply are combined, three types of behaviors can be seen in the case of DC, first the behavior of "Constant Current" RS in *Figure 37*, where the orange line which describes the V-A characteristics at the middle of the line without the help of an FL, then it can be seen a progress with the implementation of FL of *120* mm^2, *240* mm^2, and *480* mm^2, respectively.
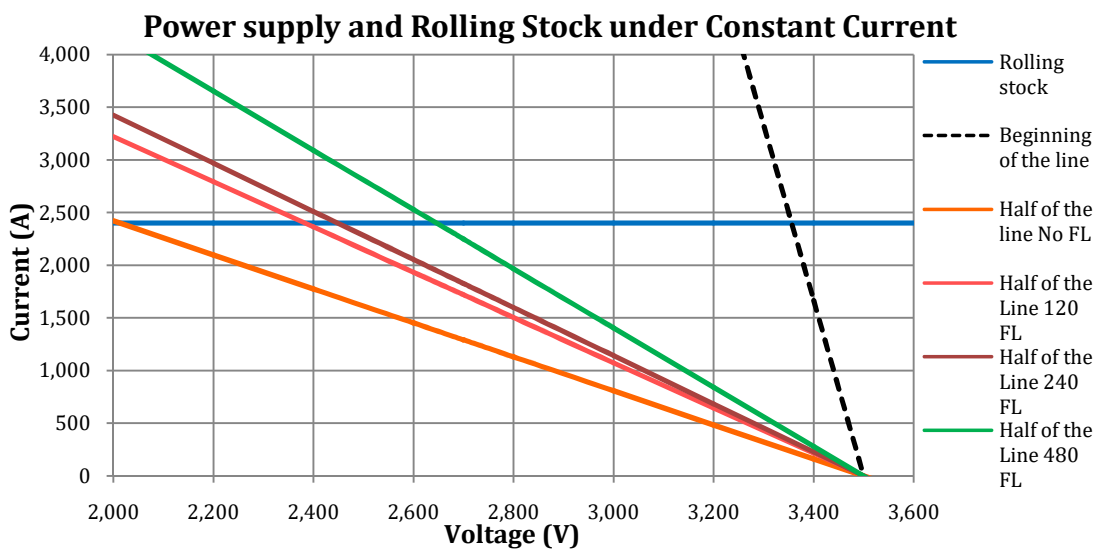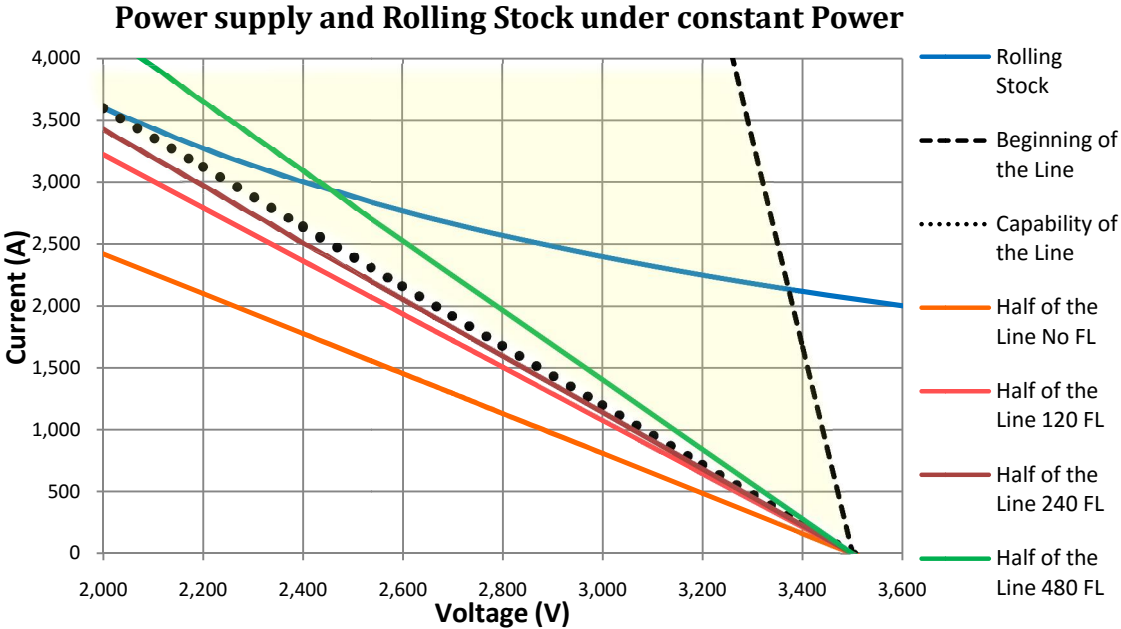

Figure 37 - V-A Characteristics of the Power Supply and the Rolling Stock without FL and with different diameters of FL on 3kV DC System with constant Current

(Source: Authors own work)

And here it is where the things get more interesting. In *Figure 38* is a new line that has to be taken into account, the "Capability of the Line" which describes the ability of the system to stand up under the required "Constant Power" of the Rolling Stock.

Those lines which are outside of the light yellow area, the cases in the middle of the line without FL (orange), with an FL of *120* (red) and *240* mm^2 (dark red) respectively, requires a huge value of current under lower voltages, bringing the system to collapsed state.

This effect can be monitored in further point 5.2.2. in *Figure 46*, *Figure 47*, *Figure 48*. The case of "Half of the Line with an FL of *480* mm^2", the green line which is inside the yellow "permitted" area is further described in *Figure 49*

Figure 38 - V-A Characteristic of the Power Supply and the Rolling Stock without and with different diameters of FL on 3kV DC System under constant Power
(Source: Authors own work)

In the case of "Automatically Regulated" Rolling Stock, it can be seen in *Figure 39*, that the V-A characteristics describes the state of current and power outside of the yellow area, but the collapse of the system, thanks to this regulation of Power, can be prevented, so the train will adapt to the capability of the supply without taking down the system.
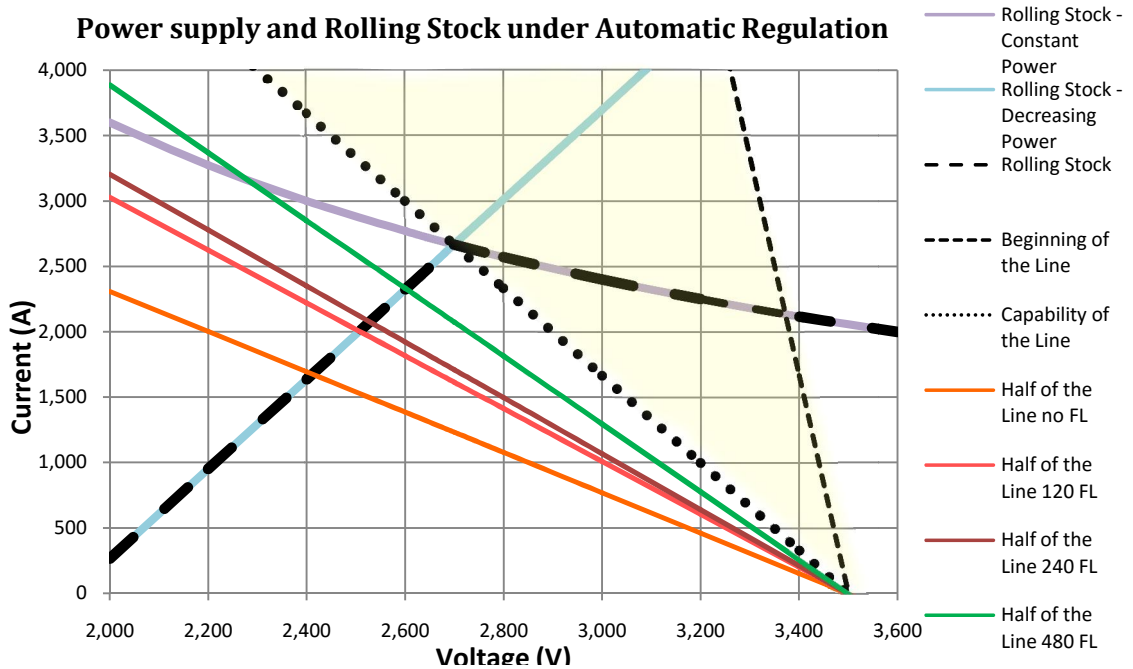
Figure 39 - V-A Characteristic of the Power Supply and the Rolling Stock without and with different diameters of FL on 3kV DC System under Automatic Power Regulation

(Source: Authors own work)

In the case of AC systems, it shows a more likable behavior in technical terms of the Capability of the Line, in *Figure 40* can be observed the status of the CT (blue), an HS in a CT Infrastructure (purple) and an HS in a HS Infrastructure (green).
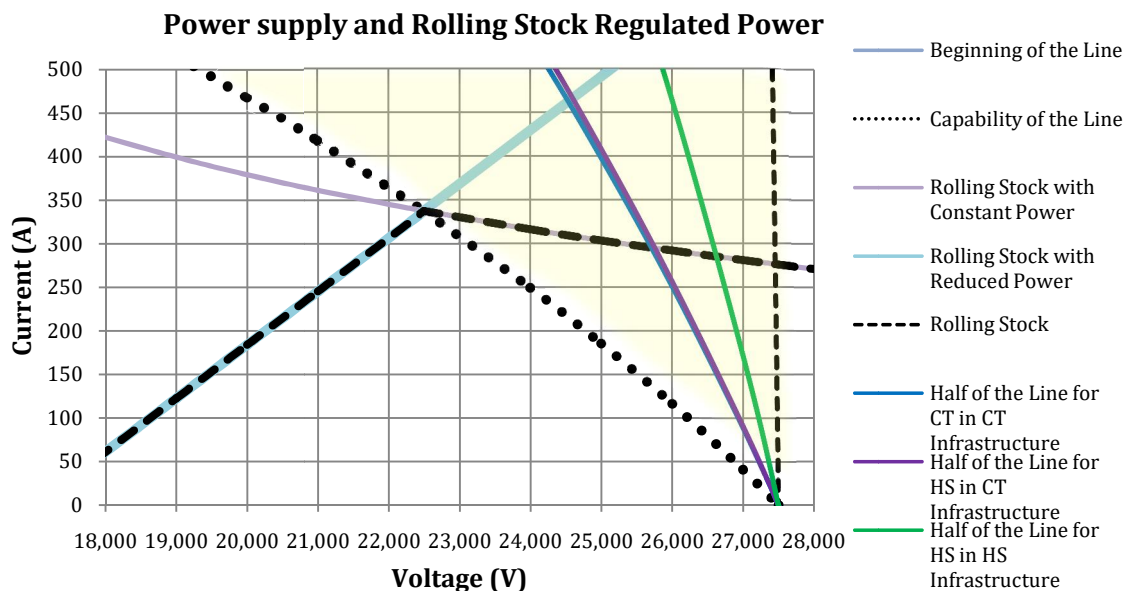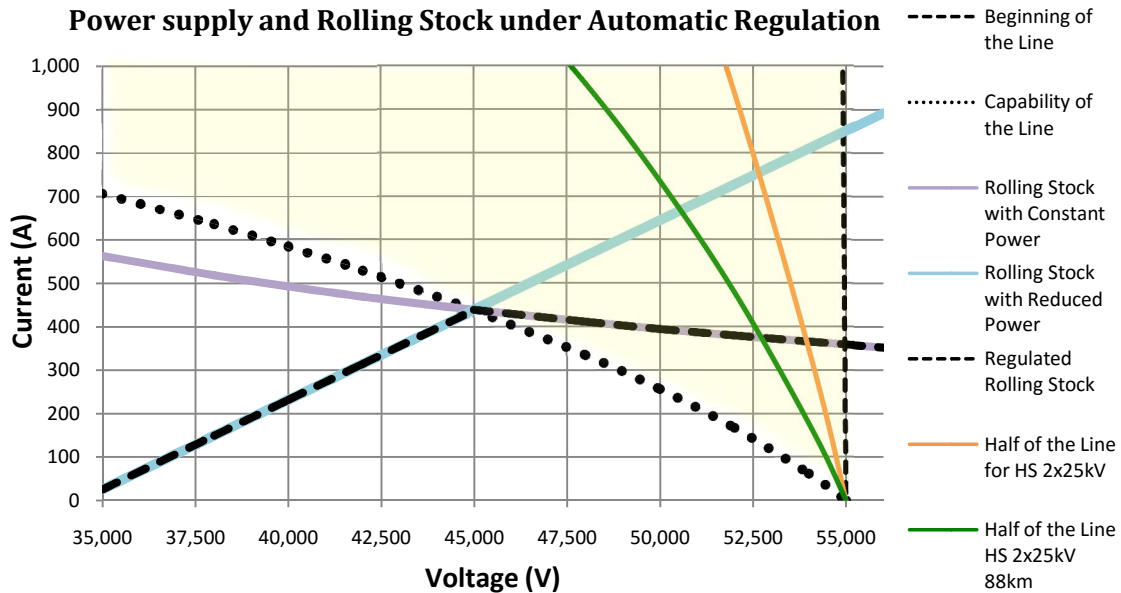

Figure 40 - V-A Characteristic of the Power Supply and the Rolling Stock without and with different diameters of FL on 25kV 50Hz AC System under Automatic Power Regulation

(Source: Authors own work)

The next trains to analyze are shown in *Figure 41*, are the cases of HS with a supply of 2x25kV at a distance of 44km (orange), and HS 2x25kV at a distance of 88 km (green).

Both graphs *Figure 40* and *Figure 41* are Automatically Regulated.

Figure 41 - V-A Characteristic of the Power Supply and the Rolling Stock without and with different diameters of FL on 2x25kV 50Hz AC System under Automatic Power Regulation for HST
(Source: Authors own work)

5.2   Results for the DC OCLs

At this point are the plots of a single Rolling Stock passing through the rail, from one substation to another in a 3kV DC system, tracing the graphic description of Power Losses, Current and Voltage drops in every kilometer of the trajectory under "Constant Current", "Constant Power" and "Automatically Regulated" Trains.

5.2.1 Rolling Stocks with Constant Current

In *Figure 42* can be seen the Constant Current taken by the train, the Voltage Drop almost reaching the minimum permitted Voltage and the Power Losses caused by them.
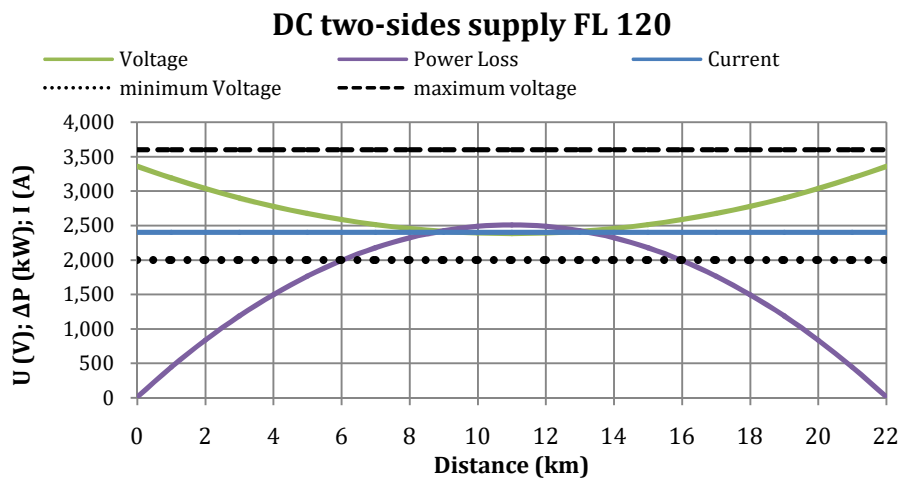
With the implementation of an FL of *120* mm^2 the Voltage Drops and its Power Losses are shown in *Figure 43*.

This effects caused by the Voltage drops in the OCL are improved with the implementation of FLs of *240* mm² and *480* mm², which can be observed in *Figure 44* and *Figure 45*.
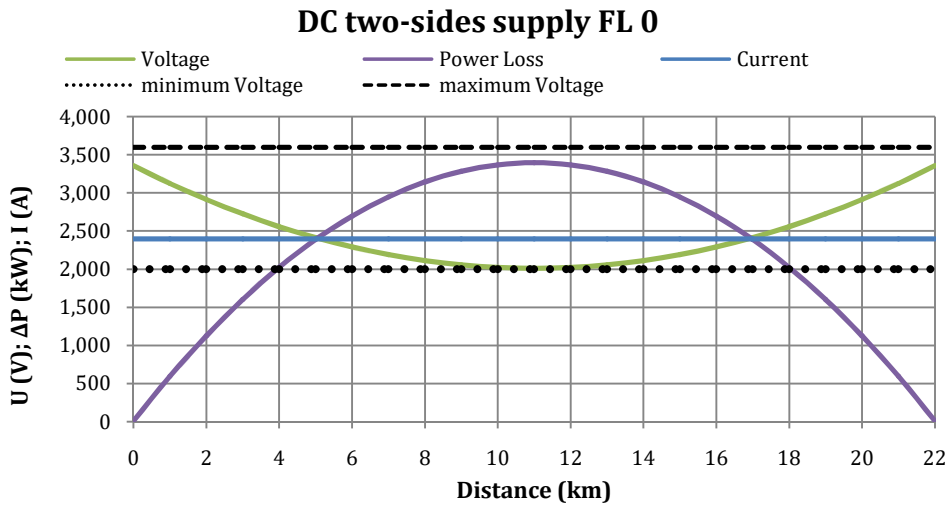
Figure 42 - DC Supply without Feeder Line under constant current

(Source: Authors own work)

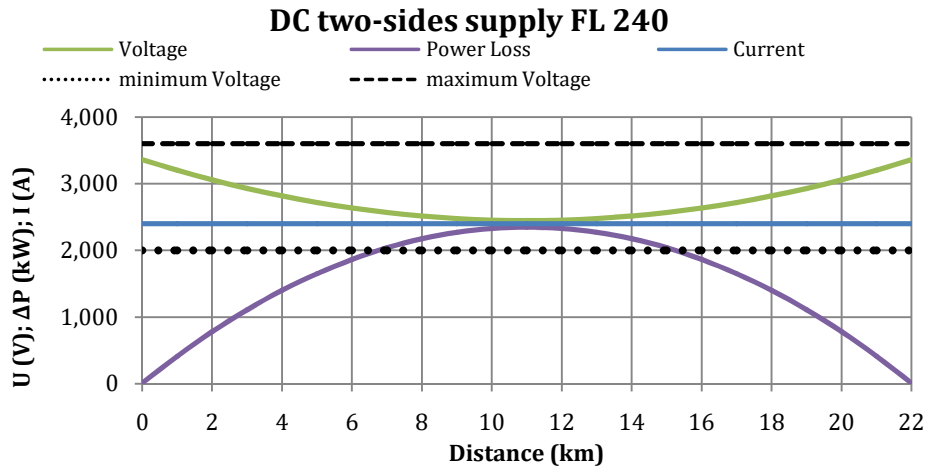*Figure 43 - DC Supply with a 120 mm² FL*

(Source: Authors own work)

DC two-sides supply FL 240

Figure 44 - DC Supply with a 240 mm² FL under constant current

(Source: Authors own work)
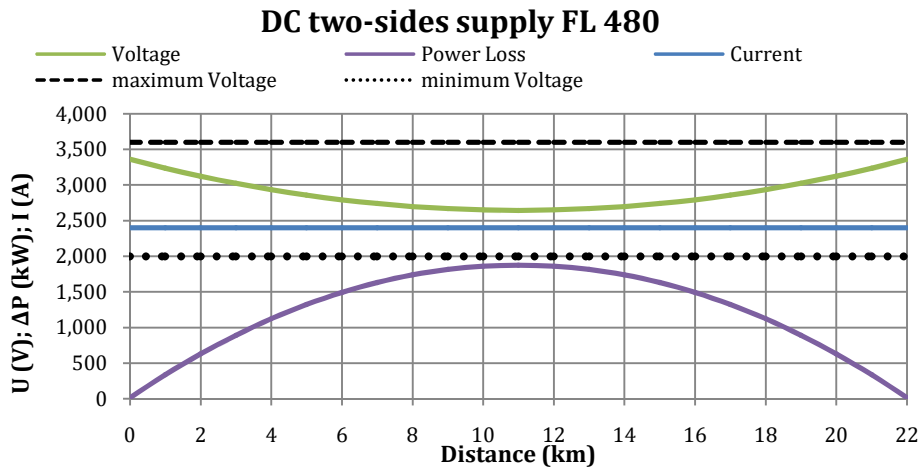
DC two-sides supply FL 480

Figure 45 - DC Supply with a 480 mm² FL under constant current

(Source: Authors own work)

5.2.2 Rolling Stocks with Constant Power

When the Rolling Stocks work absorbing Constant Power from the Power Supply, it causes the system to collapse as it was shown in point 5.2.2, in *Figure 38*.

In *Figure 46* is shown the behavior of a Train taking constant Power from the Supply, which brings with it the necessity of the Train to absorb a really high value of current, under lower voltage, generating huge power losses and collapsing the system after a distance of 5 km.
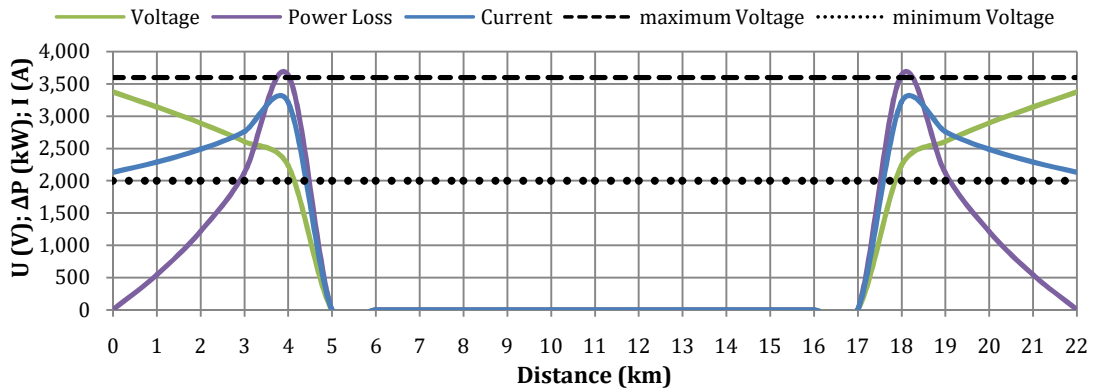
DC two-sides supply FL 0 (P)

Figure 46 - DC Supply without Feeder Line under constant Power

(Source: Authors own work)

After the implementation of FL of *120* mm^2 in *Figure 47*, *240* mm^2 in *Figure 48* the collapse of the system occurs after 3 km and 4 km respectively comparing with previous *Figure 46*. Only after the application of an FL of *480* mm^2 the system can overcome that possible breakdown as is seen in *Figure 49*.

DC two-sides supply FL 120 Cu (P)

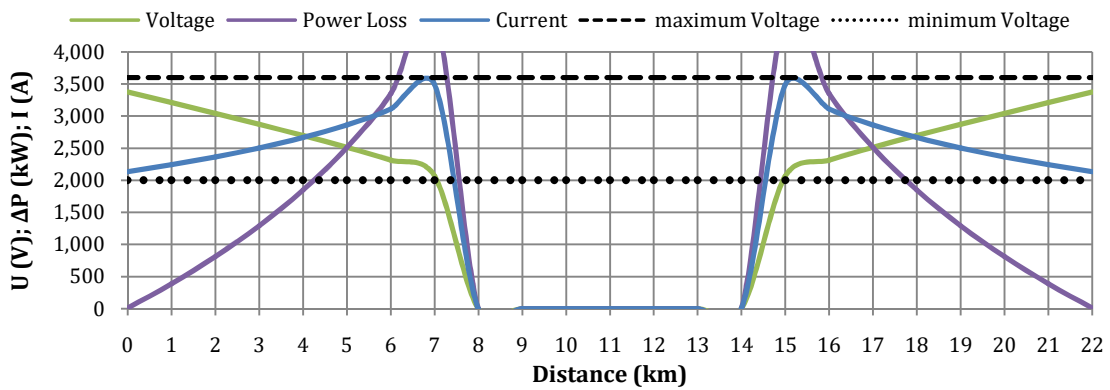*Figure 47 - DC Supply with a 120 mm^2 under constant Power*

(Source: Authors own work)
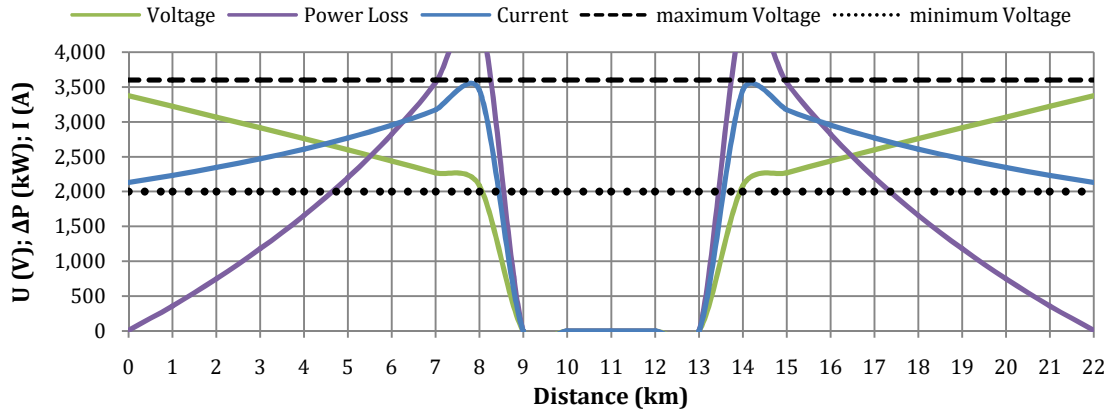
DC two-sides supply ZV 240 (P)

Figure 48 - DC Supply with a 240 mm² under constant Power

(Source: Authors own work)

DC two-sides supply FL 480 (P)

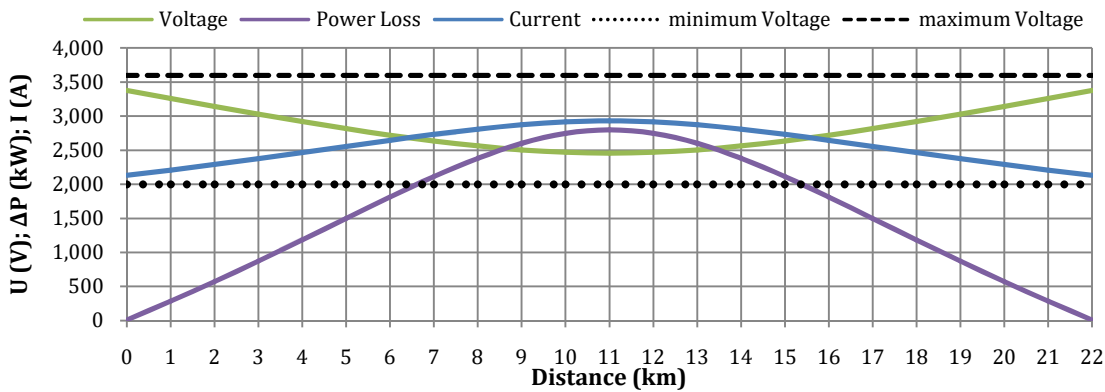*Figure 49 - DC Supply with a 480 mm² under constant Power*

(Source: Authors own work)

5.2.3 Rolling Stocks with Automatic Regulation

In the case of Automatically Regulated Rolling Stocks, the voltage drops can be seen in *Figure 50*. Without the implementation of FL there is a voltage drop about 31% of the voltage from the power supply, in the case of an FL of *480* mm², the voltage drop, reaches a value of 25%.
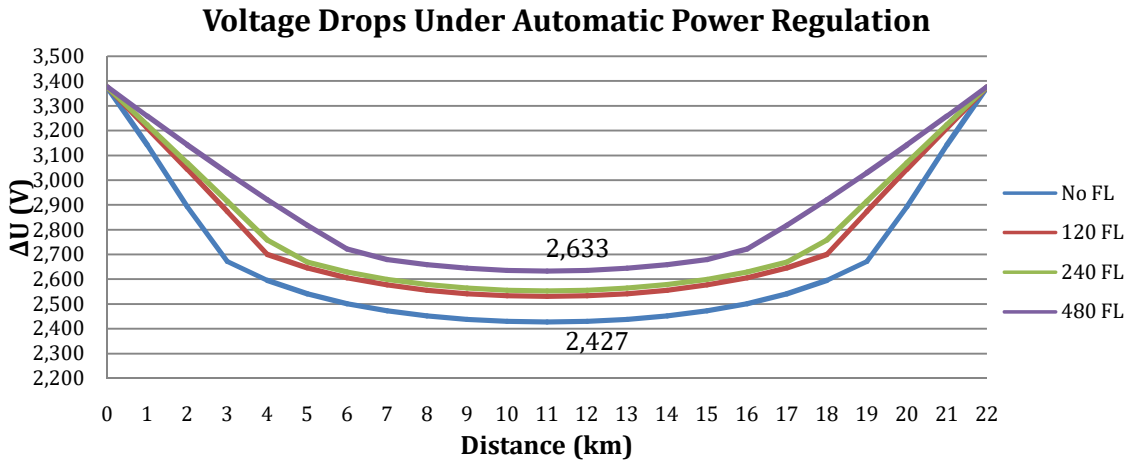
Voltage Drops Under Automatic Power Regulation

Figure 50 - Voltage Drop under Automatic Power Regulation for different diameters of FL

(Source: Authors own work)

In the case of power losses caused by the voltage drops, which are in *Figure 51*, a reduction of the area can be observed when an FL of *480* mm^2 is implemented, in comparison with the system without FL and with smaller diameters of FL.

Power Losses Under Automatic Power Regulation
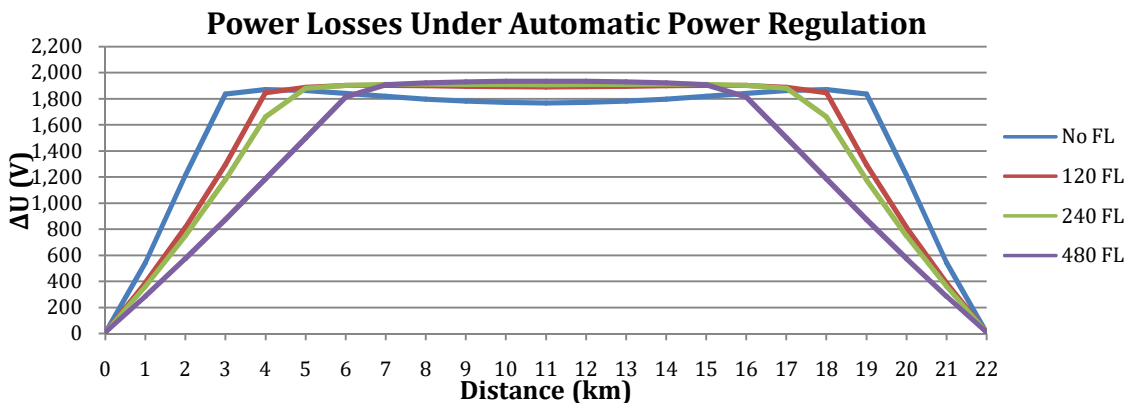

Figure 51 – Power Losses under Automatic Power Regulation for different diameters of FL

(Source: Authors own work)

5.3 Results for the AC OCLs

At this point are the plots of a single Rolling Stock passing through the rail, from one substation to another in a 25kV and 2x25kV 50Hz AC systems, describing the graphic description of Power Losses, Current and Voltage drops in every kilometer of the trajectory under "Constant Current" and "Automatically Regulated" Trains.

Figure 52 reveals the Voltage Drops at different kind of trains for a distance of 44km. The lowest value is reached by the HS in CT Infrastructure, a voltage of 22086 V, because it works with a power of 16MW, when the HS Infrastructure is implemented the voltage drops

improves to a value of 24680 V. The CT with a power of 6MW in a CT Infrastructure reaches the value of 25640 V. When the 2x25kV system is applied, the voltage drops are improved to a value of 26930 V.

AC One-side supply
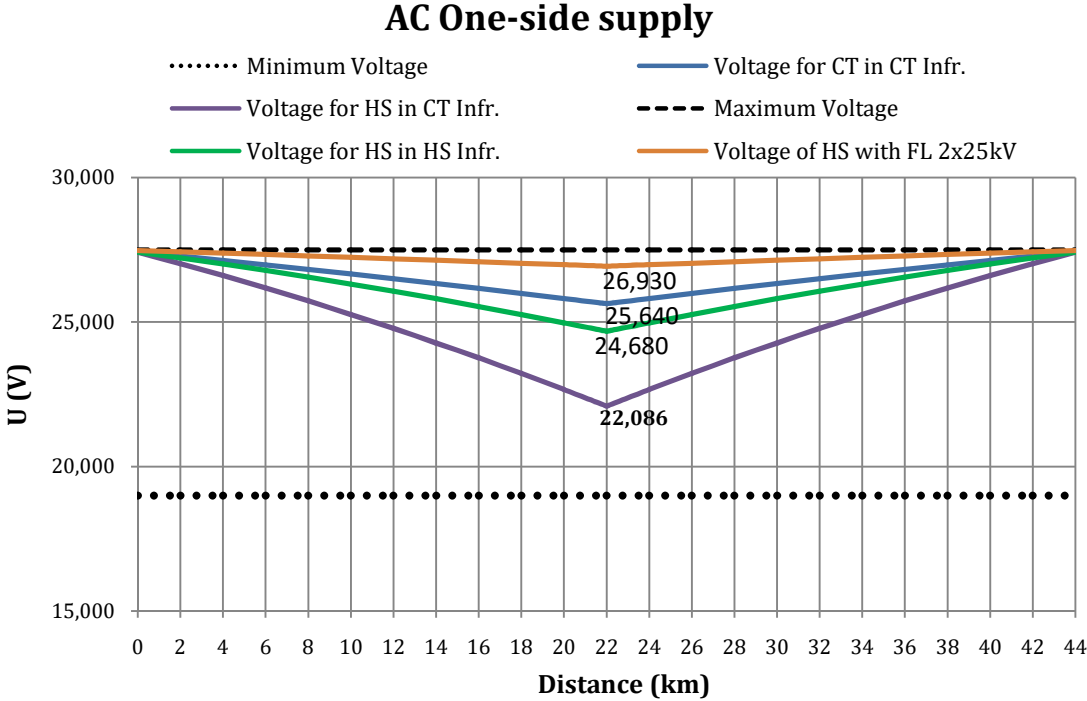
Figure 52 - Voltage Drops for AC systems for different trains, with and without FL
(Source: Authors own work)

In *Figure 53* are traced the Power losses caused by the Voltage Drops previously described in *Figure 52*.

The highest value is given by the HS Train in a CT Infrastructure. That Loss is twice reduced with the implementation of an FL of *240* mm^2, and with the application of a system of 2x25kV, the power losses are reduced up to 8 times. The power losses caused by the CT in a CT Infrastructure are quite similar to the HS 2x25kV.
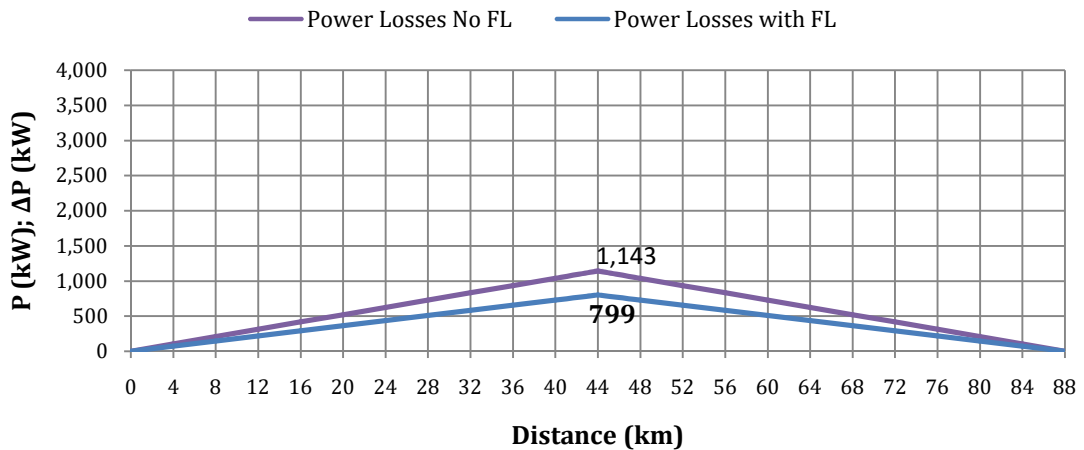
Power Losses on the OCL

Figure 53 - Power Losses for AC Systems for different trains, with and without FL

(Source: Authors own work)

If we have two power substations and a supply of 2x25kV for High-speed Trains, and the reinforcement with a diameter of 240mm² for the FL, it is possible to increase the distance between two substations, the *Figure 54* plots the Power Losses in a distance between substations of 88km, with a Power loss about 799kW which is only twice as big as the power losses for HS 2x25kV with FL for a distance of 44km shown in previous *Figure 53*.

Voltage drops at AC One-side supply 2x25kV

Figure 54 - Power losses for AC Systems for HS 2x25kV 50Hz in a distance of 88km

(Source: Authors own work)

The voltage drop in the same section of supply, shown in *Figure 55* reaches its minimum at 52606 V, the drop is only about 2394V which is only the -4,35% of its maximum value 55kV.

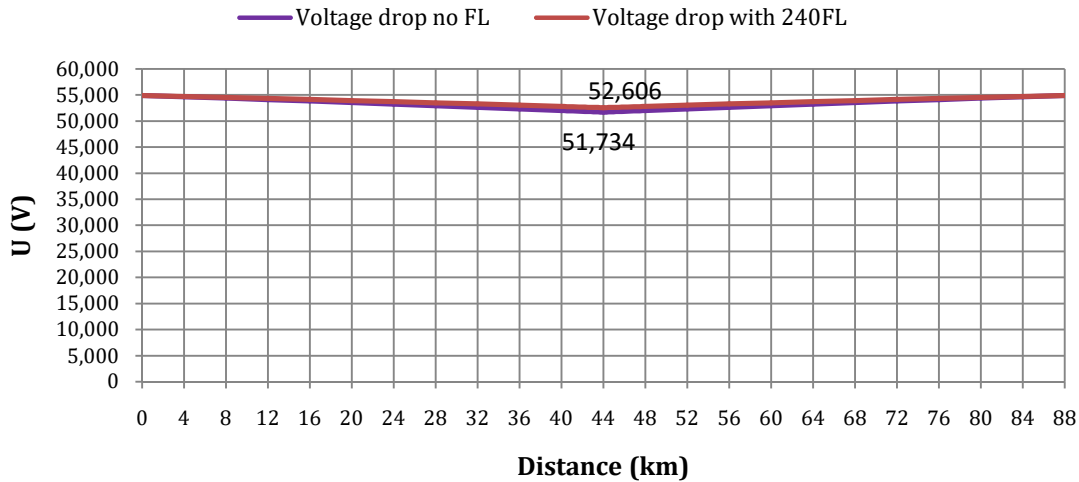
Power Losses at AC One-side supply 2x25kV

Figure 55 – Voltage drops for AC Systems for HS trains 2x25kV 50Hz in a distance of 88km

(Source: Authors own work)

5.4 Behavior of the OCL under n-Trains traveling between two substations in 25kV 50Hz AC System

Here are the plots of n-Trains traveling between two Substations, in a distance of 55km, supplied from One-side. *Figure 56* describes the supply for Two Trains of 24MW each, this is the maximum Power that can be achieved for Two Trains without passing the permitted minimum voltage, reaching a value of 19043V.

The *Figure 57* plots the Power and Voltage drop under the influence of 2 Trains of 16MW traveling through the same section, reaching a 22428V as its lowest point. The *Figure 58* shows that the maximum Power value for 4 Trains passing through this section of 55km is 12,5MW reaching the lowest voltage of 19043V. The *Figure 59* shows that the maximum Power value for 6 Trains is 8,7MW each, reaching the lowest voltage at 19058V. In *Figure 60* for 8 Trains is 6,85MW each reaching 19017V and in *Figure 61* for 10 Trains is 5,7MW each reaching 19105V.
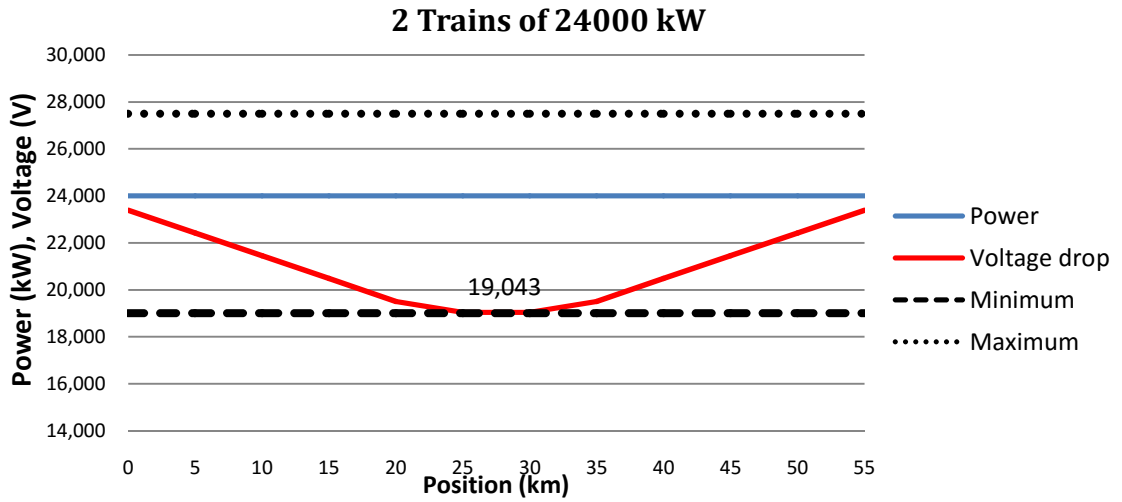
Figure 56 - Two Trains of 24MW each passing through a section between Substations
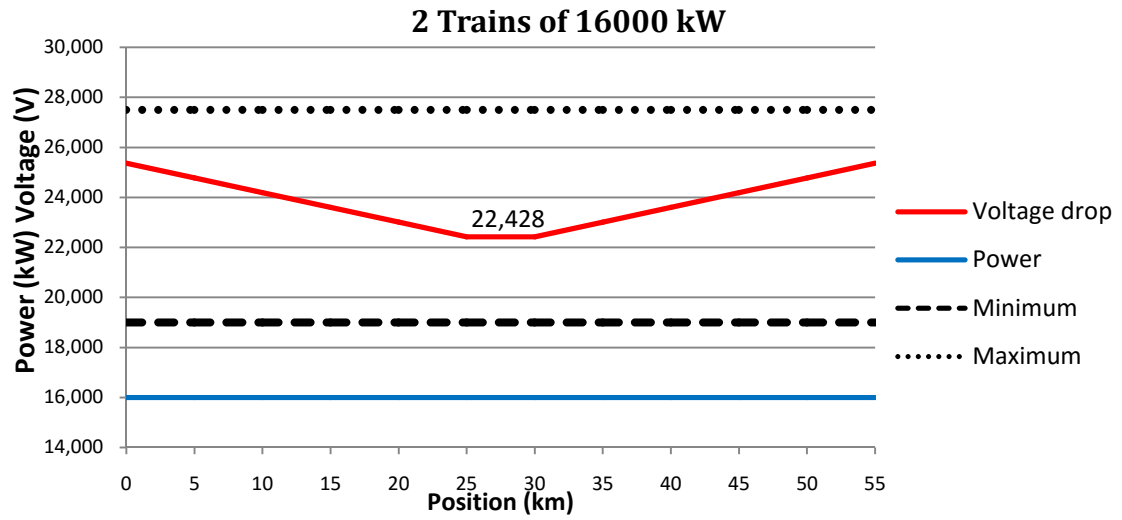
(Source: Authors own work)

Figure 57 - Two Trains of 16MW each passing through a section between Substations
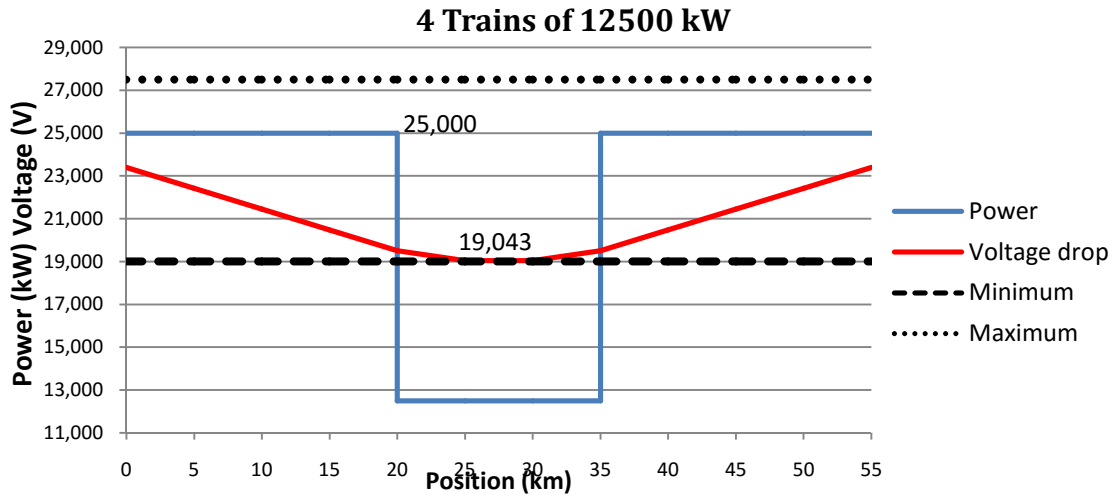
(Source: Authors own work)

Figure 58 - Four Trains of 12,5MW each passing through a section between Substations
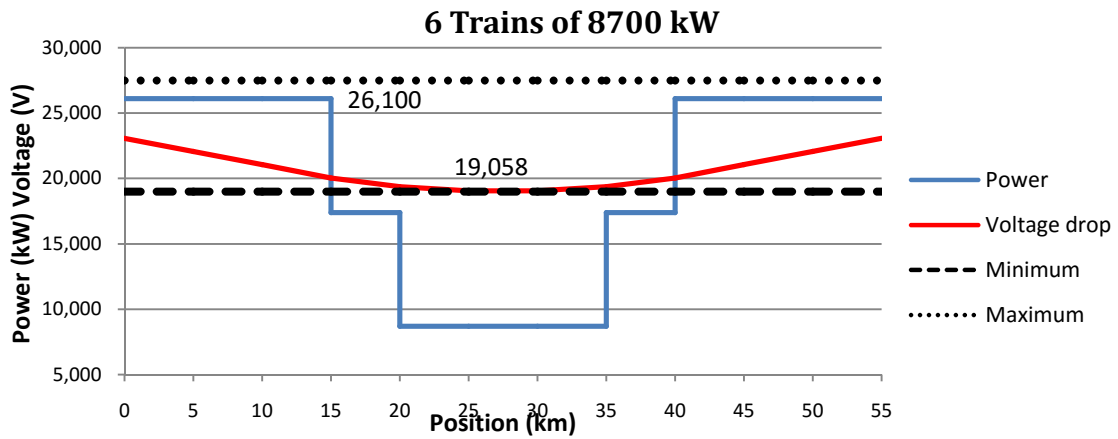
(Source: Authors own work)

Figure 59 - Six Trains of 8,7MW each passing through a section between Substations
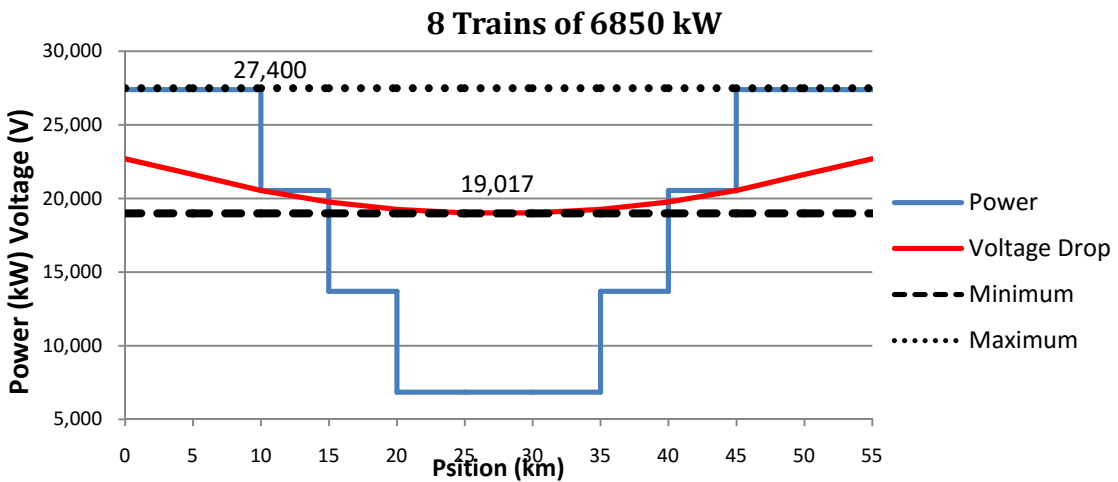
(Source: Authors own work)

Figure 60 - Eight Trains of 6,85MW each passing through a section between Substations

(Source: Authors own work)
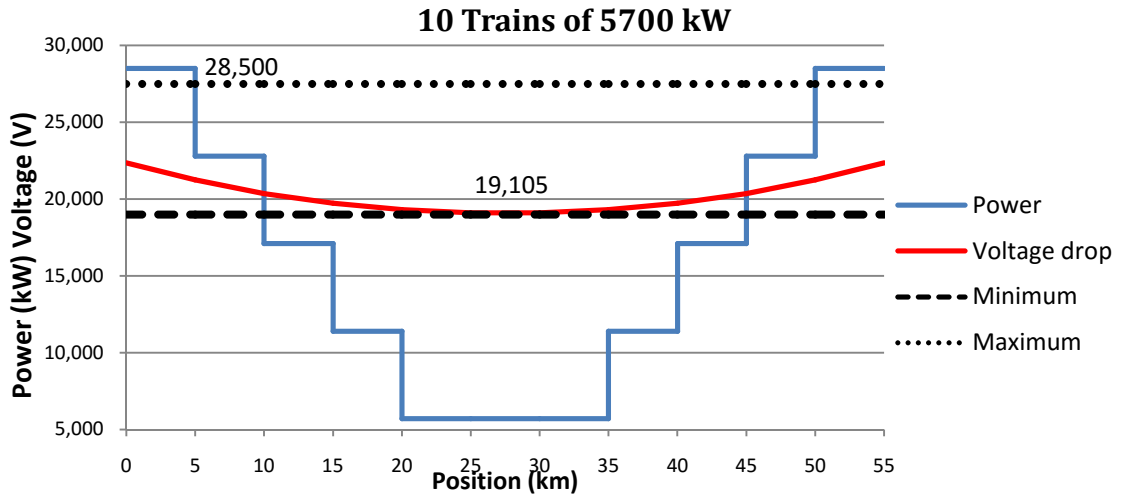
Figure 61 - Ten Trains of 5,7MW each passing through a section between Substations

(Source: Authors own work)

These calculations were made under a relative value of resistance $r_r = 0{,}17 \ \Omega/Km$ and relative value of the reactance $x_r = 0{,}46 \ \Omega/Km$, These values can be modified according to the properties of the Line to be calculated.

5.5 Phasor diagram of the system

Figure 62 - Phasor Diagram of the Vehicle and the Secondary of the Transformer under a power factor of cos ϕ = 1

(Source: Authors own work)

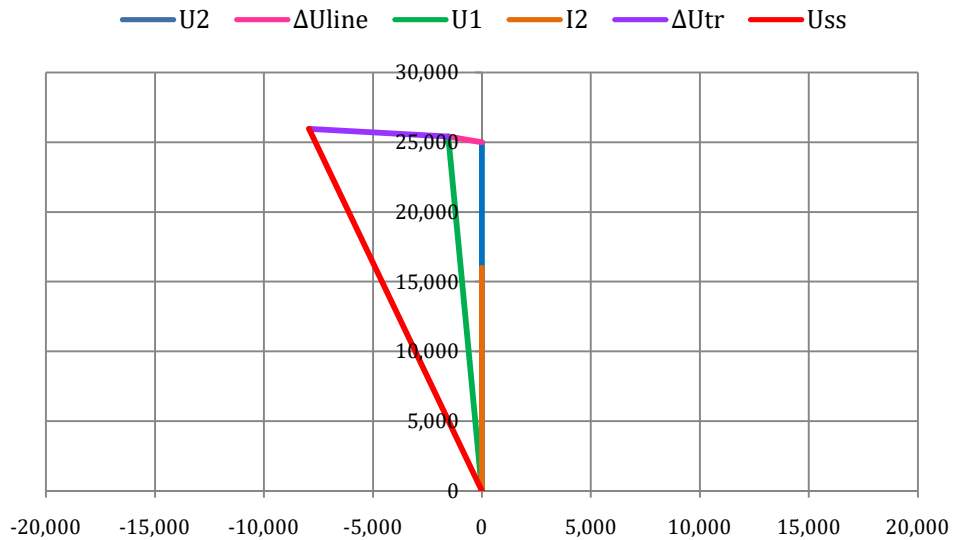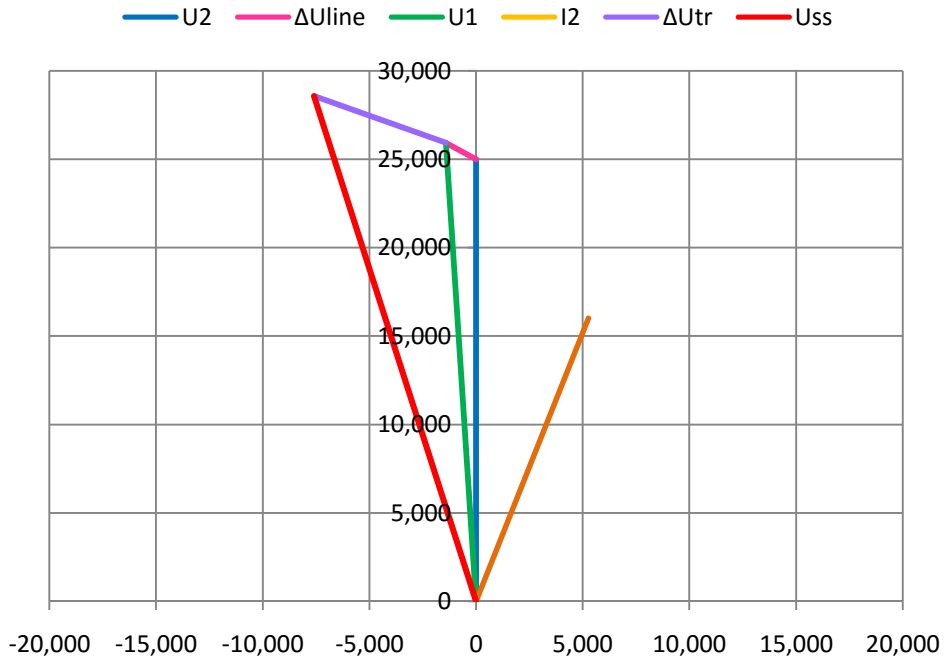*Figure 63 – Phasor Diagram of the Vehicle and the Secondary of the Transformer under a power factor*

of cos ϕ = 95

(Source: Authors own work)

6   Conclusion

At the beginning of this research was the explanation of the basic principles of Rolling Stocks, their type of traction and their parts. The second part was focused on the technology implemented for the Overhead Contact Lines, the main classification, the description of the system's physical capabilities according to the parameters of each part of the Catenary. Also, the behavior of the Voltage and Current, the effect of Frequency, the possibility of Regenerative braking and the different solutions applied to reduce the unbalance of the systems.

The improvement in aerodynamics of the rolling stocks helped tremendously to achieve the fabrication of rolling stocks with a power up to 8MW per unit. For these requirements of higher power consumption, it was necessary to implement higher Voltages. In this work it was proven that the DC systems are not compatible with speeds higher than 300km/h, therefore, the implementation of 25kV 50Hz was applied first, then the 2x25kV 50Hz.

The development of high-quality technologies as IGBT converters and more efficient traction motors and the symmetric compensators for the OCL, all brought together the improvement of the power factor of the system, reducing the energetic losses in the Overhead Contact lines, which represents not only Economical Losses for the Transportation Companies, but also an impact on the efficiency of the Electrical Systems, thus an impact on the environment.

Another way for the reduction of Power Losses and Voltage drops is the implementation of Feeder Lines in the AC OCL to reinforce the systems.

This work leads an open point to research other new ideas for the future of High-Speed Power Supplies.

7 References

[1]   J. Westin and P. Kageson, "Can high speed rail offset its embedded emissions?,"
Transportation Research Part D, Elsevier Ltd., 17 (2012) 1-7..

[2]   J. Åkerman, "The role of high-speed rail in mitigating climate change - The Swedish case
Europabanan from a life cycle perspective, Transportation Research Part D: Transport and
Enviroment," KTH (Royal Institute of Technology), Stockholm, May 2011.

[3]   ABB, "Powering the world's high-speed rail networks, ABB and the railway industry.,"
ABB, [Online]. Available: http://www.abb.com. [Accessed 12th May 2016].

[4]   A. Zhengqing, Z. Yuge, L. Shuping and G. Shibin, "Modeling and Simulation for Traction
Power Supply System of High-Speed Railway," IEEE, [Online]. Available:
http://ieeexplore.ieee.org.

[5]   M. Taniguchi, "High Speed Rail in Japan: A Review and Evaluation of the Shinkansen
Train," The University of California Transportation Center. Working Paper UCTC No. 103,
University of California, Berkeley, California., April 1992..

[6]   B. Feigenbaum, "High-Speed Rail in Europe and Asia: Lessons for the United States,"
Reason Foundation, May 2013.

[7]   E. Communities, "The Trans-European High-Speed Rail System, Luxembourg: Office for
Official Publications of the European Communities," 2004. [Online]. Available:
http://ec.europa.eu. [Accessed 12 May 2016].

[8]   I. Barrón, J. Campos, P. Gagnepain, C. Nash, A. Ulied and R. Vickerman, "Economic
Analysis of High Speed Rail in Europe," Ginés de Rus, Fundación BBVA, Spain, 2009.

[9]   E. Union, "High-speed Europe," Luxembourg: Publications Office of the European Union,
2010. [Online]. Available: http://ec.europa.eu. [Accessed 12th May 2016].

[10]   D. Albalate and G. Bel, "High-Speed Rail: Lessons for Policy Makers from Experiences
Abroad," Research Institute of Applied Economics (IREA), Barcelona, Spain, 2010.

[11]   SIEMENS, "Technical and administrative barriers for rail traffic," Siemens, 2016. [Online].
Available: http://www.mobility.siemens.com/mobility/global/en/interurban-mobility/rail-
solutions/locomotives/vectron/boundlessness/technical-barriers/pages/technical-
barriers.aspx. [Accessed 21 Apil 2016].

[12]   Boora, A. A., Zare, Firuz, Ghosh, Arindam, Ledwich and G. F., "Applications of power
electronics in railway systems. In Proceedings Australasian Universities Power Engineering
Conference (AUPEC 2007)," IEEE, Prth, Western Australia, 2007.

[13]   M. Salido, M. Abril, F. Barber, L. Ingolotti, P. Tormos and A. Lova, "Domain-dependent
distributed models for railway schedulin," Knowledge-Based Systems 20 (2007) 186–194.,

2007.

[14]   ABB, "Traction motors – Making trains fly, ABB Motors and Generators," [Online].
         Available: https://library.e.abb.com. [Accessed 14 May 2016].

[15]   P. Harrop and J. Harrop, "Electric Vehicle Traction Motors, Belt Driven & Integrated
         Starter Generators 2016-2026," April 2016. [Online]. Available: http://www.idtechex.com.
         [Accessed 14th May 2016].

[16]   S. Midya, D. Bormann, T. Schütte and R. Thottappillil, "Pantograph Arcing in Electrified
         Railways—Mechanism and Influence of Various Parameters—Part I: With DC Traction
         Power Supply," IEEE Transactions on power delivery, Vol. 24, No. 4, 2009, 2009.

[17]   J. Sadílek, „ENVIS Praha Město," Sekce Útvaru rozvoje města hl. m. Prahy, June 2001.
         [Online]. Available: http://envis.praha-
         mesto.cz/rocenky/DZ_OO/pril_practexty/BK03/2_MHD1.pdf. [Přístup získán 8 Feb 2016].

[18]   "Railsystem.net," 2015. [Online]. Available: http://www.railsystem.net/pantograph/.

[19]   "Transforming Energy into Speed. Siemens Transformers," SIEMENS AG, [Online].
         Available: http://www.pfisterer.com/download_download_en/d_2198_en.pdf. [Accessed 8
         Feb 2016].

[20]   UIC, "www.railway-energy.org," 2003. [Online]. Available: http://www.railway-
         energy.org/static/IGBT_28.php . [Accessed 21 May 2016].

[21]   B. J. Baliga, The IGBT Device. Physics, Design and Applications of the Insulated Gate
         Bipolar Transistor, Raleigh, NC, USA: North Carolina State University, 2015.

[22]   A. Fuchs, Siemens, September 2015. [Online]. Available:
         http://lme.epfl.ch/files/content/sites/lme/files/users/wetter/private/pdf_divers/em05/invitat_p
         ap/modern_propulsion.pdf.

[23]   L. Talafous, „Elektrická trakce," 02 May 2015. [Online]. Available:
         http://www.educon.zcu.cz/rservice.php?akce=tisk&cislomodulu=2015050204. [Přístup
         získán 5 Dec 2015].

[24]   P. doc.Ing. Radovan Doleček, Trakční napájecí soustavy, Pardubice: Universita Pardubice,
         2015.

[25]   F. S. O. o. Germany, "Verkehr, Eisenbahnverkehr/Betriebsdaten des Schienenverkehrs,"
         2016. [Online]. [Accessed 26 March 2016].

[26]   S. AG, "Static VAr Compensator (SVC "Clasic")," SIEMENS AG, [Online]. Available:
         http://www.energy.siemens.com/hq/en/power-transmission/facts/static-var-compensator-
         classic/#content=Details. [Accessed 11 May 2016].

[27]   S. AG, "Active Balancer," SIEMENS AG, 2014. [Online]. Available:
         http://www.mobility.siemens.com/mobility/global/en/rail-solutions/rail-electrification/ac-

traction-power-supply/converter/pages/rab-plus.aspx. [Accessed 11 May 2016].

[28]   O. A. E. Association, "OVE Austrian Electrotechnical Association," 2013. [Online]. Available: https://shop.austrian-standards.at/. [Accessed 13 April 2016].

[29]   D. Prof. Ing. Dr. Štěpán Matěna, Výroba a rozvod elektrické energie, Praha: SNTL - Nakladatelství Technické Literatury, 1975.

[30]   "The trans-European high-speed rail system," 2004. [Online]. Available: http://ec.europa.eu/transport/modes/rail/interoperability/doc/2003_high_speed_rail_tsi_guid e_en.pdf. [Accessed 5 Dec 2015].

[31]   "Railways through Europe," 16 January 2014. [Online]. Available: http://www.bueker.net/trainspotting/voltage_dc.php. [Accessed 24 March 2016].