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Simulation Model for Driving Dynamics, Energy Use and Power Supply

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Dissertação para a obtenção do grau de Mestre em
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Resumo

O objetivo deste trabalho é o de simular a interação entre o sistema de alimentação de tração elétrica e o planeamento dos veículos de tração.

Para efetuar a simulação do sistema de tração elétrica foram utilizados modelos bem como métodos de cálculo simplificados para a dinâmica de condução e uso de energia do veículo e para o sistema de alimentação elétrico da rede de energia.

Preliminarmente houve necessidade de efetuar uma análise detalhada aos softwares comerciais existentes com o intuito de se poderem analisar as diversas aplicações bem como as demais funcionalidades. Os modelos e os métodos de cálculo utilizados pelos mesmos foram igualmente objeto de estudo sendo de igual modo caracterizados. A maioria das aplicações existentes usam normalmente dois tipos de modelos (macroscópico ou microscópico). Embora o modelo microscópico apresente maior complexidade será este que reproduz a operação real do sistema ao longo do tempo.

Conforme foi referido anteriormente os métodos de calculo estudados tiveram como principal objetivo a obtenção do conhecimento de interligação do sistema do veículo de tração com o sistema de alimentação de tração elétrica.

Verificou-se que os softwares comerciais usam primariamente métodos interativos. Por forma a reduzir a complexidade da simulação do sistema de tração, houve necessidade de analisar outro tipo de métodos de cálculo não interativos, tanto para o planeamento dos sistemas de alimentação como para a energia necessária nos sistema de alimentação resultante do consumo dos veículos de tração, mediante o seu tipo bem como a quantidade de tráfego previsto.

Através da análise efetuada foi possivel identificar os aditivos necessários para a criação dos modelos desenvolvidos assim como a sua interligação com os métodos de cálculo aplicados, garantindo que o resultado obtido através da simulação efetuada seja o mais próximo ou o mais aproximado do desejado.

A caracterização do veículo de tração é um fator preponderante neste sistema, por isso efetuou-se um estudo detalhado onde são realizadas comparações entre os diversos tipos de tecnologias existentes para a regulação e controlo dos motores de tração e a sua transmissão. Através da sua caracterização foi possível analisar a sua influência no sistema e implicações das tecnologias aplicadas, sendo igualmente possível desenvolver metodologias de previsão dos diversos níveis de eficiência, aspetos térmicos, sistemas auxiliares dos veículos de tração bem como os dos tipos de travagem existentes nos diversos veículos de tração.

Após a sua caracterização seguiu-se o desenvolvimento de metodologias para o cálculo do consumo energético do veículo de tração.

Para o cálculo do consumo energético houve necessidade de caracterizar o tipo de resistências existentes que se opõem ao movimento do veículo bem como o consumo dos serviços auxiliares durante o tempo de operação.

Devido às suas características as resistências que se opõem ao movimento do veículo podem ser divididas em quatro grupos diferentes: resistências mecânicas, aerodinâmicas, inércia e de inclinação.

Normalmente o cálculo do consumo energético dos veículos considera o consumo dos serviços auxiliares constantes ao longo do tempo, como tal foi proposta uma metodologia para o cálculo dos serviços auxiliares, variável ao longo do tempo de operação e da época sazonal.

Por forma a minimizar a complexidade do estudo consideraram-se valores médios de temperatura que dependeram da época sazonal bem como dos valores médios do consumo dos serviços auxiliares tanto para locomotivas como para carruagens ferroviárias.

A soma das resistências mais o consumo dos serviços auxiliares durante o tempo de operação resultam no consumo energético total do veículo de tração.

A escolha adequada do sistema de alimentação e as suas características técnicas implicam um conhecimento prévio do próprio sistema. Como tal foi necessário caracterizar os diversos sistemas de alimentação de tração ferroviária existentes através dos seguintes parâmetros: o tipo de tensão e frequência, o tipo de corrente e o contacto utilizado para a alimentação dos veículos ferroviários. Para o último ponto apenas foi considerada a catenária, sendo este o tipo de alimentação de contacto mais usual nos sistemas ferroviários.

Um factor crucial para o dimensionamento do sistema de alimentação bem como para o planeamento do tráfego ferroviário será o conhecimento prévio do consumo de energia bem como os limites de tensão admissíveis em cada sistema de alimentação, como tal é necessário cumprir criteriosamente os limites preestablecidos pelas seguintes normas EN 50163 e IEC 60850.

Outro ponto importante para o dimensionamento do sistema de alimentação é o tipo de corrente a aplicar no sistema de alimentação, um conhecimento prévio da demanda do tráfego ferroviário é necessário, por forma a se poder optar pela decisão mais acertada. Outro factor importante para o sistema de alimentação é o tipo de alimentação proveniente das centrais de produção, podendo esta ser centralizada ou descentralizada, dependendo normalmente da distância ao ponto a alimentar bem como da demanda de tráfego. Embora não tenha sido considerado neste trabalho, o autor considera que os factores mencionados acima requerem um estudo prévio de avaliação económica num futuro trabalho.

Após o conhecimento global do sistema de energia ferroviário seguiu-se o desenvolvimento e implementação dos modelos simplificados assim como de métodos para o cálculo do trânsito de energia, com o intuito de simular o sistema de energia ferroviário através da interligação do sistema de alimentação com o planeamento dos veículos de tração. A sua caracterização bem como a interligação entre sistemas assume diversas metodologias de cálculo interagindo com vários procedimentos distintos.

A caracterização dos veículos de tração no seu percurso específico é efetuado através do software *Pulzufa*, embora o consumo dos mesmos veículos de tração seja calculado através de um método não interativo, o método de cálculo *Aubepine*.

A aplicação do método de cálculo *Aubepine* requer um conhecimento antecipado ou uma estimativa de consumo dos veículos de tração no seu percurso efetivo. Através do software *Pulzufa* estimou-se esse consumo no percurso efetivo escolhido devido à não existência de dados, sendo essa a principal razão para o autor recorrer ao software referido.

O cálculo do trânsito de energia é realizado através de uma análise nodal, por meio da aplicação de um método não interativo conforme o proposto.

Como referido anteriormente, os modelos que caracterizam a rede de alimentação foram apenas utilizados pelo autor como modelos simplificados por forma a reduzir a complexidade do sistema inerente, além disso, algumas suposições adicionais foram implementadas por forma a obter resultados viáveis e por forma a validar o modelo de simulação do sistema de energia ferroviário.

O algoritmo de cálculo utilizado relevou algumas limitações nas aproximações obtidas, conforme se pode verificar no cálculo do comprimento máximo entre as substações de tração.

Embora os resultados obtidos tenham sido satisfatórios para a simulação efetuada (1×15 kV; 16,7 Hz), estes, apenas poderam ser considerados como uma primeira aproximação, podendo mesmo ser caracterizados como cálculos preliminares onde não seja necessária uma particular precisão no cálculo ou um conhecimento detalhado do sistema de tração ferroviária.

Computacionalmente a ferramenta de cálculo implementada mostrou-se menos amigável em comparação com os softwares analisados, embora possa ser considerada uma alternativa viável devido à rápida convergência bem como à configuração dos parâmetros aplicados.

Com o intuito de melhorar a ferramenta de cálculo e transpondo algumas limitações que se verificaram nas simulações efetuadas, o autor propõe alguns melhoramentos referidos em diversos pontos desta dissertação.

A dissertação foi parcialmente elaborada durante um estágio Erasmus realizado no ano 2011/12 na University of Stuttgart, Department of Railway and Transportation Engineering, sob co-supervisão do Prof. Dipl. –Ing. Dieter Bögle e do Dipl. –Ing. Jochen Rowas.

Esta dissertação proporciona um conhecimento geral do sistema de tração ferroviário, podendo servir como base de desenvolvimento em trabalhos futuros.

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I would like to thank Ph.D. Miguel Chaves for all the support and great willingness in accepting me as my tutor.

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Abstract

The aim of this thesis is to simulate the interaction between the traction power supply system and the traction vehicles planning.

Models and calculation methods for driving dynamics, energy use and traction power supply systems are developed in order to simulate the traction power system. In these models are included functionalities as the efficiency degrees, thermal aspects and auxiliary systems of the traction vehicles.

The choice of an adequate power supply system and their technical characteristics implies a previous study on the power flow calculation in order to do the accurate option for the railway transportation demand.

The presented models for the power supply characterization in alternating current, assumes several methodologies and interacts with several distinct procedures.

The characterization of the traction vehicles behavior in the specific route uses the *Pulzufa* software, although the traction vehicles consumption over the route is calculated through a non-interactive method called *Aubepine* method.

The power flow calculation is carried out through the nodal analysis, using a non-interactive method. In addition some further assumptions are implemented to obtain more workable outcomes in order to validate the simulation model for the conventional single-phase feeding system.

The main contribution of this thesis is the approximate model which simulates the interaction between the traction power supply system and the traction vehicles schedule thought a non-interactive method in order to reduce the system complexity and the computational calculation times.

Keywords: Power Flow, Railway System, Traction System, Traction Vehicles, Railway Simulation Tools.

Resumo

O objetivo deste trabalho é simular a interação entre o sistema de alimentação de tração elétrica e o planeamento dos veículos de tração.

Por forma a simular o sistema de tração elétrica são usados modelos e métodos de cálculo para a dinâmica de condução, para o uso de energia e ainda para o sistema de alimentação elétrica. Nestes modelos estão incluídas funcionalidades tais como: níveis de eficiência, aspetos térmicos e sistemas auxiliares dos veículos de tração.

A escolha adequada do sistema de alimentação e as suas características técnicas implicam um estudo prévio do cálculo do trânsito de energia, por forma a se poder efetuar a escolha correta para a demanda do transporte ferroviário.

Os modelos apresentados para a caracterização do sistema de alimentação em corrente alternada, assume diversas metodologias e interage com vários procedimentos distintos.

A caracterização dos veículos de tração no seu percurso específico é efetuado através do software *Pulzufa*, embora o consumo dos mesmos veículos de tração seja calculado através de um método não interativo, o método de *Aubepine*.

O cálculo do trânsito de energia é realizado através da análise nodal, usando um método não interativo. Além disso, algumas suposições adicionais são implementadas por forma a obter resultados viáveis e por forma a validar o modelo de simulação no sistema de alimentação convencional monofásico.

O principal objetivo desta dissertação passa pela utilização de um modelo aproximado que simula a interação entre o sistema de alimentação de tração elétrica e o planeamento dos veículos de tração através da utilização de métodos de calculo não interativos, a fim de reduzir a complexidade do próprio sistema assim como o tempo de cálculo computacional.

Palavras-chave: Trânsito de Energia, Sistema Ferroviário, Sistema de Tração, Veículos de Tração, Simulação de Ferramentas de Tração Ferroviária.

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List of Abbreviations

ERTMS	European railway traffic management system
ETCS	European train control system
DRCS	Decentralized rotating converter station
DSCS	Decentralized static converter station
AC	Alternating current
DC	Direct current
AT	Auto-transformer
RB	Regional train
RE	Regional express train
IC	Intercity train
GUI	Interactive graphical user interface
PMSM	Permanent magnet synchronous motor
V/F	Voltage-frequency technique
PWM	Pulse width modulation
4QC	Four-quadrant converter
MF (DC/DC)	Medium frequency (direct current- direct current)
GTO	Gate turn-off thyristor
IGBT	Insulated gate bipolar transistor
IGCT	Integrated gate commutated thyristor

$\mathbf{S_{cc}}$	Short-circuit power
$\mathbf{Z_{network}}$	Network impedance
$\mathbf{U_{network}}$	Network voltage
cos φ	Power factor
$\mathbf{P_n}$	Nominal active power
$\mathbf{Q_n}$	Nominal reactive power
$\mathbf{S_n}$	Nominal apparent power
$\mathbf{Z_{generator}}$	Generator impedance
$\mathbf{U_{generator}}$	Generator voltage
$\mathbf{Z_T}$	Transformer impedance
$\mathbf{S_{nT}}$	Transformer apparent power
$\mathbf{U_{ccT}}$	Transformer short-circuit voltage
$\mathbf{U_{1nT}}$	Transformer primary voltage winding
$\mathbf{U_{2nT}}$	Transformer secondary voltage winding
m	Transformer transformation ratio
$\mathbf{S_c}$	Conductor cross section
Z	Conductor impedance
$\mathbf{V_n}$	Nominal voltage
$\mathbf{I_n}$	Nominal current
L	Circuit length
R	Resistance
X	Reactance
Y	Admittance
n	Number of trains

1 Introduction

1.1 Background

Nowadays the development of the railways systems associated to the structure of the railway network shows a large and fast growth on the capability of transportation.

The increase of the railway interconnecting is a commitment among several countries due to the ecological concern and grow on the transport capability.

One of the advantages from the electric train traffic is the energy consumption as the supply source, which provides lower energy consumption. Compared to the other systems is required a smaller area of land for the same capability of transportation.

Moreover the energy supply is a more attractive solution when converted to electricity, making the electric train transportation even more ecological. Furthermore the electric vehicles in comparison to other systems do not release carbon dioxide due to the electric traction development as a substitute of diesel traction[1].

With the rising of the railway traffic some questions are raised, causing numerous concerns in several countries due to the increase of trains on the track and also the inclusion of faster trains. These circumstances require a new electric railway network or its upgrade. With this increase of load flows, being a time-dependent power demand picking up and recovering energy at changing locations, the network structure and the voltage situation influences the internal load flows.[2] Due to currents and an increase in power losses with decreasing voltages, the under low voltage conditions current or power limitations of the train propulsion control can be activated with an impact on the driving dynamics as well as in the network voltage that determines the braking energy recovering decisively.[3]

Therefore the power supply system may influence the traction characteristics of the trains and the railway energy consumption. As a consequence the development and research in this area is growing massively.[4]

To improve the development is necessary to do an accurate analysis of the entire traction system.

[1] (Boullanger, 2008-2009)
[2] (OpenPowerNet – Simulation of Railway Power, 2008)
[3] (Ibid.)
[4] (Ibid.)

The modern software technology offers new possibilities to characterize and improve the simulation, therefore is necessary the interconnection among the models via appliance of consistent methods, providing valid results with satisfactory level of performance.[5]

The *Pulzufa* software was developed by the University of Stuttgart its main goal is to simulate the train traffic operation. It is a simulator, which the utilization is less friendly to handle than a commercial one. However the *Pulzufa* software determines (for a train traffic plan) the train running times and the train energy consumption, although does not integrate the module of the power supply system design.

1.2 Aim and Main Assumptions

Through the development of calculation methods for driving dynamics, energy and power supply system the aim of this master thesis is to simulate the interaction between the traction power supply system and the traction vehicles planning. Along the route it is considered the average electric power consumption as the energy produced by the regenerative braking. The energy efficiency of vehicles, the resistive force acting on the train, the speed, the track limitations and the travel time is regarded. It is also considered the impedance of the active conductors, generators and transformers in order to calculate the voltages, the currents, the losses, the power and the power flow in the bus bars and nodes.

The maximum distance between traction power substations and auto-transformers is also regarded in the calculation method.

The models and the calculation methods used in this master thesis, assumes several assumptions in order to simplify and reduce the traction system complexity as well as the computational calculation times.

In the development of this master thesis some issues were raised resulting in a necessity to upgrade the *Pulzufa* software. Considering train power systems on *Pulzufa* software the study of the railway network is more reliable reducing the initial investment of the projects, for this reason studies have to be performed conducive to evaluate the necessary requirements in order to obtain the most suitable solution. In the future the parameters can be changed since these are dependent of: the type of trains, track characteristics and traction power supply system. Therefore the obtained results through the models and the used method should be reviewed for suitable future planning’s.

[5] (OpenPowerNet – Simulation of Railway Power, 2008)

1.3 Report Structure

The first chapter is an introduction to the project, explaining and justifying the purpose of this master thesis, and detailing the structure of the report.

The second chapter introduces the comparison and valuation between different softwares and calculation methods with the aim of evaluate the necessary requirements for the development of the models and calculation methods for driving dynamics, energy use and traction power supply systems.

The characterization of the railway traction vehicles is described in the third chapter, regarding electrical traction technologies, functionalities as the efficiency degrees, thermal aspects and auxiliary systems of the traction vehicles and the traction forces applied to the vehicles.

Calculation methods of energy consumption of the electric traction vehicles are shown in the fourth chapter, including reference values for auxiliary systems consumed by cars and traction vehicles.

In chapter five the main characteristics of the most common traction power supply systems used are presented considering the DC (Direct Current) and AC (Alternating Current) power supply systems, with central and decentralized energy supply.

The power flow calculation method and models which constitute the electric traction system is presented in the sixth chapter.

The seventh chapter shows the simulations made in order to analyze and evaluate the used calculation model.

In the eighth chapter, the author assembled his suggestions for a future work and describes final conclusions of this master thesis.

Finally the bibliography of this master thesis is presented in the ninth and last chapter.

This Marter Thesis was partially elaborated, developed and written, during an Erasmus research at the year 2011/12 in the University of Stuttgart, Department of Railway and Transportation Engineering, under the co-supervision of Prof. Dipl. Ing. Dieter Bogle and Dipl. Ing. Jochen Rowas.

I would like to thank to the Department of Railway and Transportation Engineering of the Stuttgart University, the availability of documentation and the data of the Pulzufa software.

2 Simulation Tools for Railways

The earliest electric railway vehicles in the electric traction project had the purpose to determinate its movement on the electrified network, its energy consumption and its implication on the electrical railway network. The idea of connecting train traffic operation planning to the constraints of the power system is not new. For that purpose this chapter primarily presents as an introduction a general view of the interaction between different simulation softwares. Analyzes different calculation methods and models used in order to identify the necessary additions to be include in a new simulation tool.[6]

2.1 Overview of the Railway System

Since the production of the railway transportation service is an endeavor that involves many different questions ranging from the strategic infrastructure extension to the rolling stock, it is usually divided hierarchically into several stages. Depending on the problem type to be considered (Figure 1) that is the main reason of the rail simulators, each one is design to respond to a different type of concern in the railway system.[7]

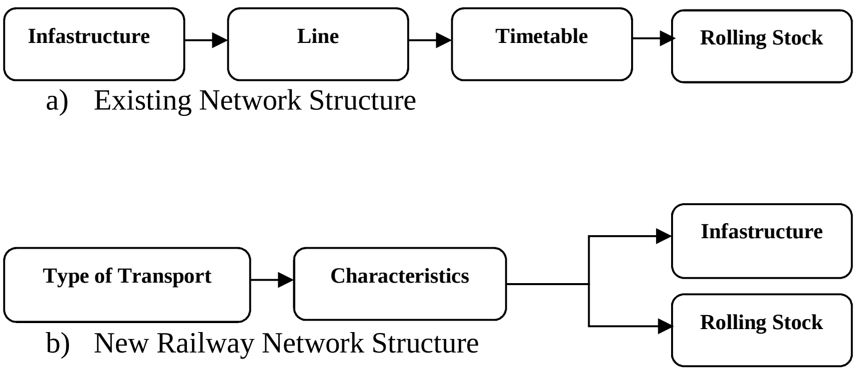


Figure 1: Structure of the railway system

However the stages are not independent of each other and cannot be considered in a purely sequential way, each stage generates a result, which is used as an input for the next stage. Based on the demand estimation, for existing networks [(a)] the railway infrastructure is a crucial step since it can be extended, modified, or reduced.[8]

A line plan consists on a set of train lines that has direct connections between two terminal stations, with additional intermediate stops. A train line also includes the specification of the type vehicle used for this service, and its frequency, in case of regular periodic services.[9]

[6] (ABRAHAMSSON, 2008)
[7] (CAIMI, 2009)
[8] (Ibid.)
[9] (CAIMI, 2009)

The next step, called the timetabling problem or train scheduling problem, is a particularly critical step in the whole railway planning process because it has a direct impact in all system.

After the timetabling stage the next step is the rolling stock stage where the technical characteristics of the vehicle are set, defining a series of trips that operates in sequence by the same rolling stock unit. Usually it operates in a cyclic basis, over a certain period, however the same unit could be assigned to a different set of trips in the next period for further planning.[10]

For planning new railway networks [(b)], the railway structure primarily assumes distinct types of stages in order to enhance the railway system in an effective way. The main concern for the new railway networks planning is the type of transport and its own characteristics stages. As previously mentioning the stages are not purely sequential, the railway infrastructure and the rolling stocks are planned in order to fulfill the estimation demand.

2.2 Simulation Models

The mathematical models used in the transportation system simulation tools can be characterized as macroscopic or microscopic, depending of the simulation tool used and the applied methodology.

In the following subchapters will be presented the characterization of the mathematical models outlined above.

2.2.1 Macroscopic Simulation Model

The macroscopic model uses average values to evaluate the operation of the transporting system providing a simplified description of the timetable, therefore quite similar to the published timetables that are available for passengers, in the form of arrival and departure train time's in the principal stations. The train dynamics is also simplified. The exact speed profile on the edge is not directly taken into account, as the train acceleration and braking behavior that is neglected on this level. With this approach the detail of the infrastructure and the computational requirements are lowered.[11]

2.2.2 Microscopic Simulation Model

The microscopic model replicates the actual operation of a railroad over time. Describes in detail the operation and the infrastructure database, the influence of each train as well as the impact on each other during a defined time step. This process is repeated during the simulation period. For this purpose, detail information related to the track topology and train's dynamic properties is required.

Through this model it is possible to analyze and evaluate in an early conceptual stage the possible incompatibilities in the infrastructure or in the roadmap design.[12]

[10] (Federico Barber, 10/01/2007) (Railroad Simulation Using OpenTrack) (CAIMI, 2009)
[11] (Ibid.)
[12] (Ibid.)

The microscopic simulation model can be defined in two types, asynchronous and synchronous:

- The asynchronous model simulates the network operations separately (e.g.), they set the first train and its schedule. For the following inputs the process is simultaneous repeated consequentially, without causing impacts between them.[13]
- The synchronous simulates the network operations at the same time. This provides realistic operating conditions and enables the users to apply specific parameters in order to avoid conflicts between them.[14]

2.3 Driving Simulation Tools

In this point will be carried out the characterization and functionalities of different simulation tools for driving dynamics and energy use of train runs. As the main goal of the simulation tool there are some differences in the input data depending on the used model.

Generally the driving simulation tools works as the following diagram:

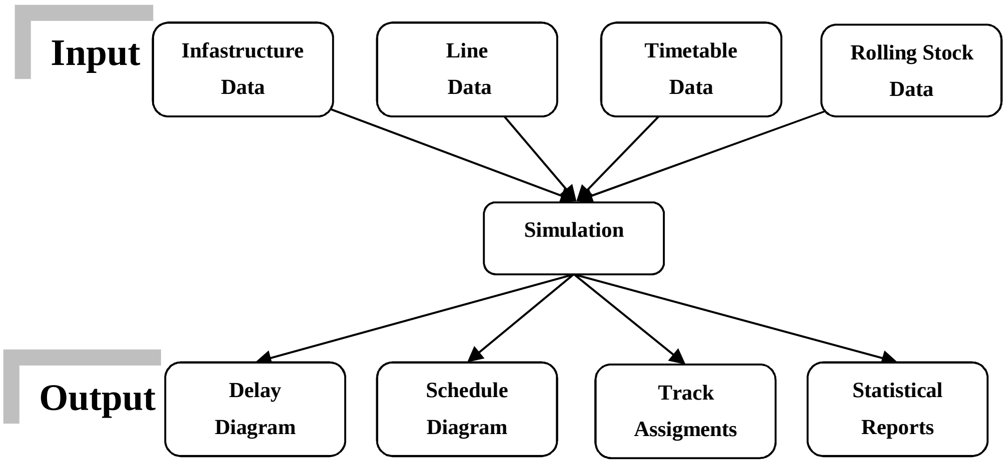


Figure 2: Driving simulation tools structure [15]

2.3.1 Pulzufa

Pulzufa, is a software developed by the University of Stuttgart. The conceptual model uses a microscopic asynchronous simulation model.

The design software uses a number of simple structural elements. The aim of this tool is to calculate the travel time calculation and its energy consumption over the programed route.

The program regards among other things, the main characteristics of the several types of vehicles with different performances during the simulated route.[16]

[13] (Federico Barber, 10/01/2007) (Railroad Simulation Using OpenTrack) (CAIMI, 2009)
[14] (Ibid.)
[15] (Eisenbahnbetriebssimulationen, 2005)
[16] (Hetzinger, 2001)

The application fields are:

- Determination of the driving dynamics characteristics;
- Analysis of driving gradients;
- Train and locomotive dimensioning;
- Mapping of new braking technology;
- Calculation of running time, consumption and energy recovering over the route;

2.3.2 Zuglaufrechnung (ZLR)

Zuglaufrechnung, is a tool developed by the SBB Company, and uses a microscopic asynchronous simulation model.

The mainstream of this tool is the effective time travel of the rolling stocks stage and the calculation of the power consumption including the auxiliary system consumption over the route. The inherent loss through the transition stages e.g. (air, tunnel and track resistances) is regarded.

This tool simulates the time train location through the rail traffic safety systems and allows an effective rail system support through a timetable optimization improving the planning process.[17]

The application fields are:

- Determination of the driving dynamics characteristics regarding energy saving;
- Driving gradients analysis;
- Train and locomotive data base and dimensioning;
- Mapping of transition stages braking;
- Calculation of running time, consumption and recovering energy of train runs;

2.3.3 Dynamis

This tool was developed by the IVE mbH, Consulting Company for Traffic and Railway Engineering Ltd., from the University of Hanover.

As the previous one this tool also uses the microscopic asynchronous model and simulates the vehicles behavior through its configuration on a given line. It is used as an researching tool for railway vehicle dynamics.

The physical basis of this infrastructure model and the technical constraints allows highly accurate travel time calculations and train energy consumption for different driving strategies.

[17] (Roos, Januar 2006)

The results provide a basic data for further planning, e.g. timetable construction, dimensioning of safety systems and development of new train technologies.[18]

The main features used in this tool provides configurable protocols for further analysis or evaluation, graphical comparison of train runs, creation and modification of the calculation parameter via dialogues and interactive graphical user interface (GUI).[19]

The application fields are:

- Determination of the driving dynamics characteristics;
- Driving gradients analysis;
- Train and locomotive dimensioning;
- Mapping of new braking technology;
- Calculation of running time and mapping with different running strategies;
- Calculation of energy consumption regarding the auxiliary systems consumption for operations and heating/conditioning power;
- Safety systems;

2.3.4 Viriato

The *Viriato* tool was developed by the SMA Company and Partner AG, it uses a microscopic synchronous simulation model, is mainly used for strategic planning purposes, i.e. adapting an infrastructure to future service concepts and coordinating several operators or products sharing the same infrastructure

This software is compose by several functionalities such as: running time calculator, timetable service, trip type analyses, rolling stock rostering, line map, calendar and track/station occupation with conflict detection, all supported by an netgraph with the representation of the railway network and their mutual relationships with a timetable. As a main concern the planning of regular interval trains and analysis of single trains, e.g. freight freeways. Allows the user to determine the level of saturation of a specified line or part of it, in percent, enables a precise validity definition for trains, specifying exactly on which day a train is running, the operational feasibility is considered, e.g. train maintenance, parked and cleaned.

It offers the definition of several speed profiles for the same infrastructure, and the calculation of the resulting running times for different train configurations.

[18] (Eisenbahnbetriebssimulationen, 2005)
[19] (2.0, Dynamis Manual)

Includes a library of numerous European engines with their tractive effort diagrams and additionally the user has the possibility to define any other design engine.[20]

The application fields are:

- Development of timetable concepts for networks;
- Determination of infrastructure and operational data (dimensions, lines and junctions);
- Detail maintenance data;
- Comparison of different timetable scenarios within the same database,
- Coordination of long distance, cargo, and regional traffic;
- Coordination of various rail traffic providers;
- Track selection of any route within a defined network;
- Estimation of the amount of train kilometers;
- Computation of the circulation demand;
- Travel time calculation and calculation of energy consumption of train;

A resume table of comparative functionalities of the simulation tools functionality it's shown in the Table 1:

Simulation Tools / **Operations**	**Pulzufa**	**ZLR**	**Dynamis**	**Viriato**
Infrastructure manager	✓	✓	✓	✓
Rolling stock manager	✗	✗	✗	✓
Timetable manager	✗	✓	✓	✓
Timetable optimization	✗	✗	✗	✗
Station manager	✗	✗	✗	✓
Capacity analysis	✗	✗	✗	✗
Sensitivity analysis	✗	✓	✓	✓

Table 1: Comparison of the simulation tools functionalities[21]

[20] (Federico Barber, 10/01/2007), (SMA company and Partner AG, 2006)

[21] (Ibid.)

The description of the operational concepts is shown below:

- **Infrastructure manager:** Manages the infrastructure data of a railway system.
- **Rolling stock manager:** Manages the rolling stock scheduling.
- **Timetable manager:** Manages the editing of train timetables date in graphic or tabulate way.
- **Timetable optimization:** Provides optimization algorithms which schedules train movements and generate a timetable in accordance with an objective function, schedule priorities and network constraints.
- **Station manager:** Assists the planners in the resolution of the problem related with routing trains through a railway station.
- **Capacity analysis:** Assess the railway capacity.
- **Sensitivity analysis:** Processes more than one scenario calculating indicators of performances in different conditions.

2.4 Identification of the Necessary Additives for a New Simulation Tool

The development of the new simulation tool aims the interaction between the railway traffic calculation module and the traction power supply system module. At this point there are improvements that can be identified and can be applied on the new simulation tool ensuring an approach of an actual railway traffic system.

These improvements can be divided into four general categories although they are not independent of each other: infrastructure, rolling stocks, schedules and operations.

2.4.1 Infrastructure

In the infrastructure category it is necessary to introduce additional data. The type of infrastructure will affect all the parameters of the railway network system. The author proposes the following additives on the simulation tool:

- It is necessary to characterize the type of power supply system used, given that the traffic capacity will be affected. The vehicle model will also be change since each railway power supply system interacts with different type of vehicles. The exploration type will also interact with the railway vehicle e.g. (neutral zones); during that section its consumption is approximately null and all traction motors must be disconnected.

- Nodes, distance and number of tracks between nodes: the introduction of this point will be reflected on different velocity levels, vehicles consumption and time travel calculations through accelerations, breakings or stops.

2.4.2 Rolling Stocks

Generally the type of rolling stocks used offers a possibility to reduce travel times and energy consumption improving the network planning. Therefore it is necessary to introduce additional data in order to improve the characterization of the vehicle and to adjust the vehicle movement to the needs of the traffic performance.

The author proposes the following additives on the simulation tool:

- It is necessary to improve the vehicle model; depending on the type of vehicle. It is crucial the characterization of the electric and mechanic energy transformations from the pantograph until the wheels. The efficiency degrees and the associated losses in those components during the route should be regarded as well as the thermal model additive should also be considered.

- To reduce the energy consumption and increase the recovery energy of the vehicle, should be considered different strategies of driving, although this point depends on the planned timetable.

2.4.3 Schedules

Due to this point it is possible to include different time travels to the same route, with an efficiency schedule construction resulting in a reduction of the time travel and the requested energy. The author proposes the following additives on the simulation tool:

- It should be regarded different trip times, dwell times, connections, turnaround times and headways and asses the exact run of each train.

2.5 Software Tools and Applying Methods of Power Supply Systems and Power Consumption on the Railway System

The analysis of the traction power system is crucial to the design and operation of an electrified railway. For different levels of traffic is used the proper power supply system. Concerning this purpose is essential the analysis of the load flows in various feeding systems and service demands in AC and DC railways power supplies.

In this point will be carried out the analysis of the used comprehensive methods and the traction power simulators related with the interaction among loads and deterministic solutions of the power network.

2.5.1 Aubepine

The *Aubepine* method uses a probabilistic analysis, the main goal of this method is the consumption calculus of the active energy power on a railway network in order to dimension the traction power supply system.

This method uses as a sample twenty trains in one-hour route and the average values of consumption during braking (regenerative braking), accelerating, stopping at stations and constant velocity (coasting) of several types of trains. This energy consumption is calculated per minute being the overall sum of the vehicles energy consumption the energy provided (in a precise minute) by the traction power supply system. Is regarded an increase of energy on high speed lines due to the high velocity of trains and the total gross load of the high speed train (IC/EC). It is also considered energy losses between the power generator and the catenary. In order to improve the capacity and stability of the network, the timetable was compressed for further capacity evaluation, this modification contributes to reduce the overall energy consumption by influencing the trains and minimizing unnecessary stops.

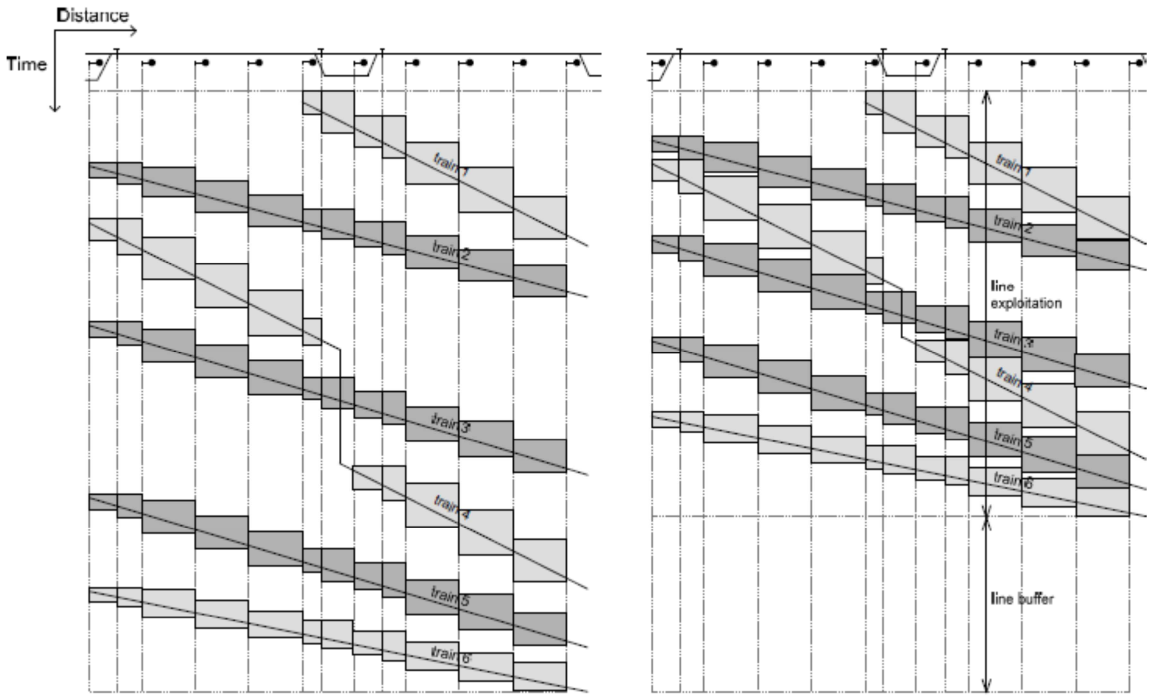
The calculation capacity can be made in two different ways, operating on the blocking time:[22]

- One possibility is to calculate the average minimum line headway from the minimum line headways of the different train combinations and the relative frequencies of these train combinations. Multiplying the average minimum line headway by the number of trains the result is the consumed capacity. That principle does not need a specific timetable but only a traffic pattern (mix of trains) that allows the user to calculate the relative frequencies of all train combinations.

- The other possibility is the consumed capacity that is derived from the original timetable by virtually moving the blocking time stairways together, as close as possible, without any buffer times and also without changing the train sequence. This principle is also known as the “compression method”.

The figure 3 presents an original [(a)] and a compressed [(b)] timetable. Through this figure is it possible to verify the main advantages (capacity consumption evaluation) with the timetable compression.

[22] (Methode Aubepine, 1995)



(a) Original timetable (b) Compressed timetable

Figure 3: Example of the original and compressed timetable[23]

Considering the fact that the parameters of the actual time travel average are unchangeable and after two correction factors that were applied on the power generator and on the energy consumed for the shortest time travels with the compression of the timetable, the obtain values regarding the sample analysis are quite similar compared with the calculated values of a software tool ZLR/SBR. Although to make a detail evaluation it is relevant to have the actual graphic of the substation energy consumption.

This method uses a simple way of calculus regarding the necessary active energy power on the railway network. The method could be improved if a more detailed input data were considered on the infrastructure (operation type of the traction power substations and interaction between them or the vehicle data such as different levels of coasting consumption), it also doesn’t make any reference for the reactive power energy demand.

The necessary active energy power was made in one node of the Suisse railway network. This node interacts with the interconnection of multiple railway lines.

The author considers this method an approach for an initial project evaluation, although this method does not reflect the correct dimensioning of the power traction substation due to the inexistent concern of the voltage drop limit as the influence of more traction power substations, different types of railway systems and safety request of energy failure in one traction power substation (criterion n-1).

The appliance of this method also requests a previous vehicles behavior study in the accurate path, limiting the method applicability.

[23] (Tobias Lindner, 2010)

2.5.2 Von H. Forwald

The main goal of *Von H. Forwald* method is the dimensioning of the traction power substations. This method regards different traction system, direct current (DC) and alternating current (AC). The analysis of this method is based in a probabilistic sample of 20 hours traffic volume per day. For the network capacity calculation was created a load factor curve with the number of trains according to the traffic volume, for that analysis it was used a traffic pattern without a specific timetable.[24]

The first analysis includes two different configurations at the same time with DC and AC traction current and the second analysis AC system includes auto-transformers. In the AC system it was regarded the single-phase system as the auto-transformer system. It was also considered voltage drops, regarding the admissible maximum voltage drop in the middle of two feeding points as the neutral zones. Some resistive factors were included such as: adhesion factor, train efficiency, rail, return conductor, compensation conductor and catenary resistance. Power factors and efficiency factors seem to be modeled independent of the vehicles velocities. It is an interesting method with its probabilistic load flow approach and with a good description of how the single-phase system and auto-transformer system works in the 16,7; 25 and 50 Hz railway power supply system.[25]

Although this method only contemplates the necessary traffic and power with constant energy flux between traction power substations; this doesn't reflexes different scenarios of power flow between power substations in the network and the influence that can cause in the system. The approximation made in this method does not characterize more nodes, railway lines or safety requests of energy failure in one traction power substation (criterion n-1) it is also not regarded on the dimensioning.

2.5.3 OpenPowerNet

The *Opentrack* is a simulation tool from the Company SMA and Partner AG. This software interconnected with the *Openpowernet* module becomes a powerful traction power system simulation software. The result of the traction power system calculation interacts directly with *Open Track*. The models of the *OpenPowerNet* and the *Open Track* replicate the complexity of the traction network in detail. The method used in the software is called, nodes method, in order to predict electrical network calculation, an interactive method is used in both models.

Is it possible to compress the timetable only with *Open Track* and further *OpenPowerNet* makes the electrical network analysis. Since the *Open Track* tool simulates timetable disruptions is it possible to analyze its influence in the electrical network through the *OpenPowerNet* tool[26]

[24] (Forwald, Von H. Baden: s.n., Elektrische Bahnen)
[25] (Forwald, Von H. Baden : s.n., Elektrische Bahnen)
[26] (GmbH, Institut für Bahntechnik)

This model is compost by several input data and functionalities such as:[27]

- Switch position and status changes of the electrical network during the simulation;
- Complete electrical network characterization and calculation, reflecting the network structure, conductor properties and the electromagnetic coupling effects;
- Input of the electrical network parameters by use of the geometrical conductor arrangement and the material properties with unrestricted configuration;
- Analysis and interpretation tools (energy, load flows, currents);
- Retroaction of electrical network calculation to train driving dynamic;
- Online-communication between operation and electrical network simulation;

2.5.4 Compatibility Between Driving Dynamic and Power Supply Methods and Software of the Railway System

In this point the main goal is to evaluate the compatibility between softwares.

The compatibility between them is possible when exits communication through an interface.

2.5.5 Compatibility Between Calculation Methods and Driving Dynamic Tools

In order to exist a communication between software and methods it is necessary to create compatible software that integrate modules. These modules need to integrate the method as well as its interface needs to be common to each other.

2.5.5.1 Compatibility Between Driving Dynamic Tools and OpenPowerNet

OpenTrack railway operation simulation is realized by a constant time step calculation.

OpenPowerNet work together in a so-called co-simulation. This means that both programs communicate and interact with each other during the simulation as presented in the figure 4 (bellow).

[27] (GmbH Federico Barber, 10/01/2007)

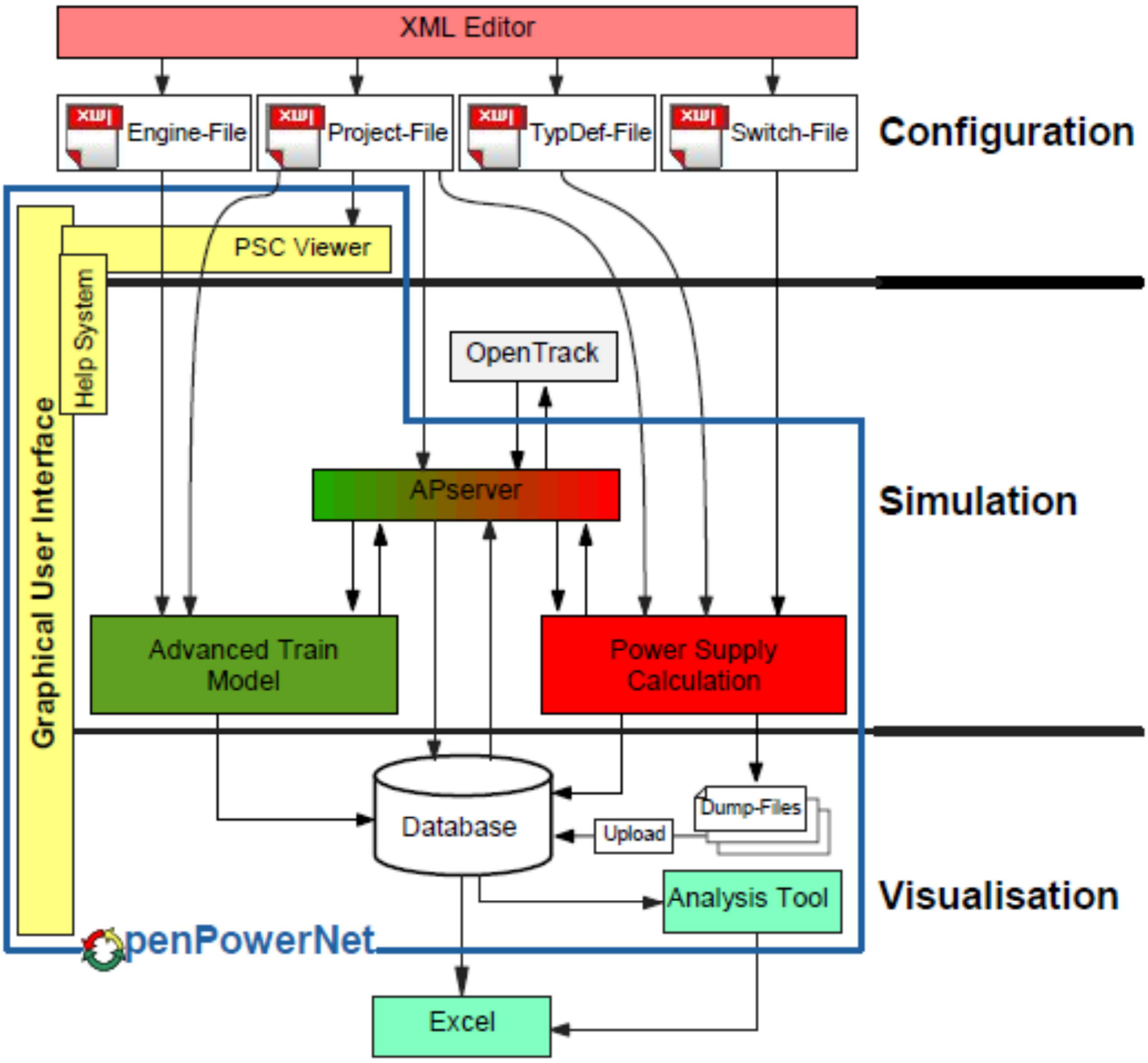


Figure 4: OpenPowerNet workflow and application structure[28]

2.5.6 Identification of the General Aspects and Components

Electric power supply systems are classified according to several characteristics: feeder systems, used by type of current (direct and alternating), power plant, by layout (circular and radial) and operating mode. The electric power supply systems also include power substations for the conversion and distribution of electric power and controlling operation of the system (step-up and step-down voltages), converting three-phase alternating current to direct current and vice versa, and providing a number of outgoing lines that differ from incoming lines. The interaction between the power supply system and the railway structure increases the complexity of the system due to the flow of energy consumption of loads during the track as well as the type of power supply exploration.

[28] (GmbH, Institut für Bahntechnik)

As an essential premise of the power supply dimensioning, the following points should be considered:

- The maximum length between traction power supply substations in the single-phase system. In the auto-transformer system the maximum length between the traction power supply substations and auto-transformer, also between auto-transformers;
- Characterize and evaluate the losses in the railway network;
- Maximum admissible voltage drops and criterion (n-1) must be regarded;
- In the energy power network must be included the energy produced by the vehicles through the regenerative braking, for the energy consumption calculation different types of vehicles should be considered as well as the timetable;
- The energy provided by the traction power substation should regard the total nominal vehicles power consumption in the feeding section of the traction power substation;
- The model must include the power flow of the traction power system;

3 Railway Traction Vehicle Characterization

The railway vehicles have suffered several changes over the last years; nowadays most of the railways vehicles and most of their systems are electric due to the global environmental concern, reduction on countries' dependency on fossil fuels imports and enhance customer benefits. The aim of this chapter is to describe the electrical systems used in the electric railway vehicles and its influence.

The system of the electrical vehicles depends on the electric power supply system and on the technology used for the traction motors control.

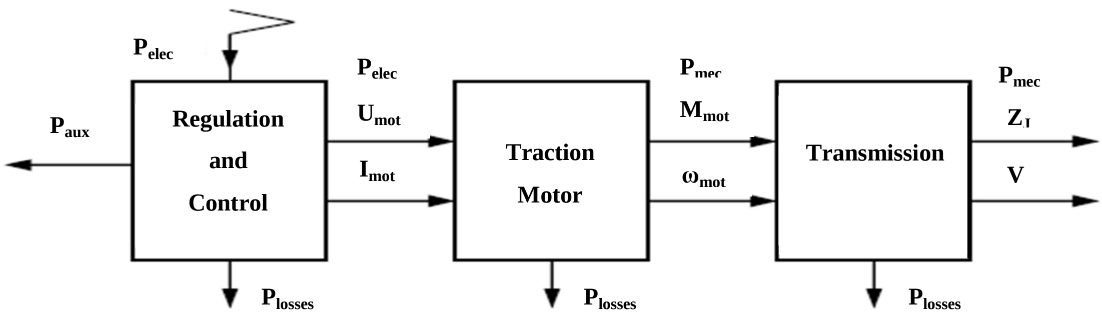


Figure 5: Process of the electrical conversion into mechanical energy[29]

The generic railway vehicle elements and types of transformation process are shown in figure 5. There are energy losses during each transformation through each stage.

3.1 Direct Current vs. Alternating Current Traction Motors

In this point a global comparison between DC (direct current) and AC (alternating current) motors will be presented. Initially the DC motors was the mainstay for electrical traction motors. The torque-speed and the simple control system for traction demands were its main advantages, however the DC motors use switches/brushes and collectors, making them less reliable and adequate for working at high speeds. The use of AC motors instead of DC motors was the first electrical change in railway vehicles. For higher power densities AC motors reduced dimensions and weight, increasing efficiency and power densities, lowering the operation costs and reducing maintenance since they don't have brushes. Nowadays, DC motors are used in special applications with lower power requirements since the controlling cost (power electronics), is lower.

Among the AC motors the motor who won major acceptance in traction propulsion was the induction motor. The asynchronous motor in comparison with the synchronous motor has a simplest construction with lower maintenance, lower volume and weight.[30]

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[29] Energy (Roger Kaller)
[30] (Fitzgerald, 2003) (Pires, 2006)

The asynchronous motor allows higher speeds with the use of power electronics; one can overcome this problem although even the control system for braking is complex and more expensive.

The higher quantity of magnetic material in the synchronous motor and an external excitation source, increases the costs, however this motor presents higher efficiency when working with factor power equal to one. This synchronous motor was used in the French TGVs and the Spanish AVEs mainly because it was the available technology at that time. The axle weight could only bear 17 tones and since the GTOs available on the market did not had the sufficient capacity, the thyristors were the only possibility; at the same time there were a concern due to its turn-off. The utilization of a special circuit for the turn-off increased the inverter weight since the synchronous rotor is a magnet as well as the required voltage that was used to make the thyristors turn-off through the rotor.[31]

The next revolution related with the electric traction motors will be made thought permanent magnet motors use. Although the rotor is made with permanent magnets, the permanent magnet synchronous motor (PMSM) uses identical stator windings as an asynchronous motor. Without rotor windings the benefits are obvious, *Joule* losses are minor and the efficiency increases. Since the excitation is made with high production levels of energy (permanent magnets), the maintenance is lower and the torque will be higher, also the volume of the machine will decrease considerably.[32]

Since the mechanical efforts are lower the motor reliability increases producing a smooth torque, a low vibration and noise. Moreover, they are very attractive since they can operate with a wide range of speeds, without the need of independent ventilation.

The main disadvantages of this type of motors are the considerable high coercivity cost from the permanent magnetic material, and the possibility of demagnetization.

Due to the development of new permanent magnet materials the (PMSM) is a wise choice comparatively with the asynchronous traction motor as it can be analyze thought the following table.

Characteristics / Type of Motor	**PMSM**	**Asynchronous Motor**
Rotational speed [rpm]	1480	2055
Current[A]	86	157
Output [kW]	83,6	114,4
Torque [Nm]	540	532
Efficiency [%]	94,2	87,9
Power factor [%]	87,6	79

Table 2: Comparison between PMSM and asynchronous motor[33]

The related motor models can be found in the source[34].

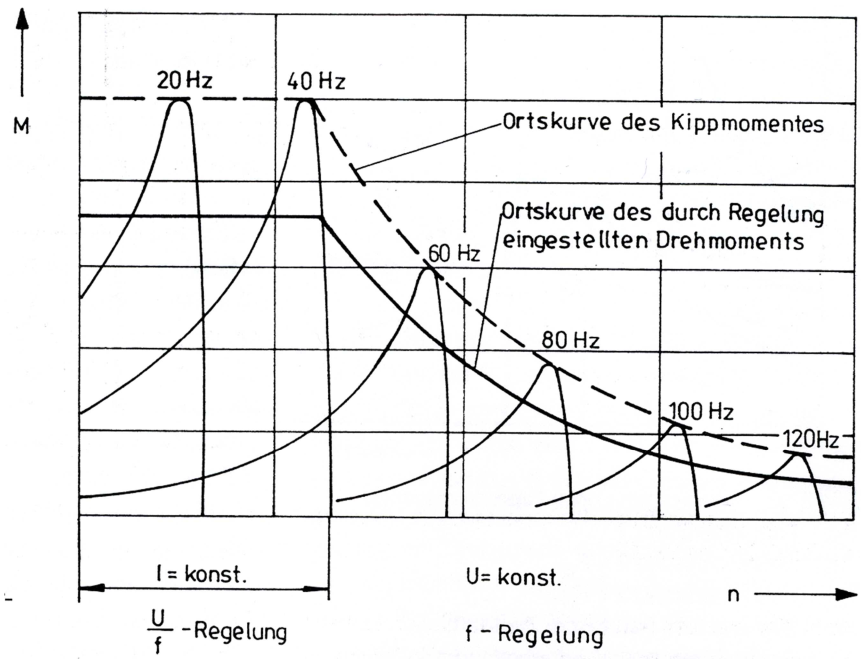
[31] (What drives electric multiple units, 1998)
[32] (Ibid.)
[33] (Matsuoka, et al., 2002-10-09)
[34] (Fitzgerald, 2003), (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)

3.2 Regulation and Control

The introduction of power electronics and drives in railway vehicles caused the major technology revolution in this sector. For many years the control of the motor only provided speed control and load variation adaptation. With the introduction of power electronics and microprocessors this control provides even more tasks, with an higher precision and efficiency. The aim of this point is to make a global characterization of the regulation and control used in traction vehicles.

3.2.1 Traction Converters

The main purpose of traction converters is to control and convert the electrical energy of the vehicle. Through new semiconductor devices development is possible to obtain a higher efficiency in energy conversion processes. Nowadays the most common technique used to control traction motors is called the voltage-frequency (V/F) technique, it is possible to vary the speed by acting on the frequency and control the torque, modifying the voltage supply as can be seen in the following figure.



I Motor current
U Voltage
F Frequency
M Torque (equivalently, power)
N Engine revolutions (equivalently, speed)

Figure 6: Different torque curves for different frequencies[35]

Since the direct converters are no longer used in traction, the indirect converter consists in a rectifier (AC-DC transformation), filter (DC voltage smooth) and inverter (DC-AC transformation).

The electronic power rectification (AC-DC transformation) in nowadays is made with IGBTs and GTOs technology, it uses the pulse width modulation technique (PWM) it also works as an inverter with reverse power flow controlling the DC voltage (or current).

35 (Ramos, 2011)

The main goal is to reduce the harmonic distortion by changing actively the waveform of the input current and also improving the power factor. These rectifiers are also known as (PWM) regenerative rectifiers.[36]

The aim of the inverters is to convert DC to AC current. Commonly inverters are used in traction with polyphase topologies. The switchable devices used in these inverters are also IGBT with a (PWM) modulation for the same reason explained in the previous paragraph. With this method it is possible to change the frequency but not voltages amplitude.

The main circuit diagram of 300 series Shinkansen locomotives uses this type of converter as it shows in the following figure.

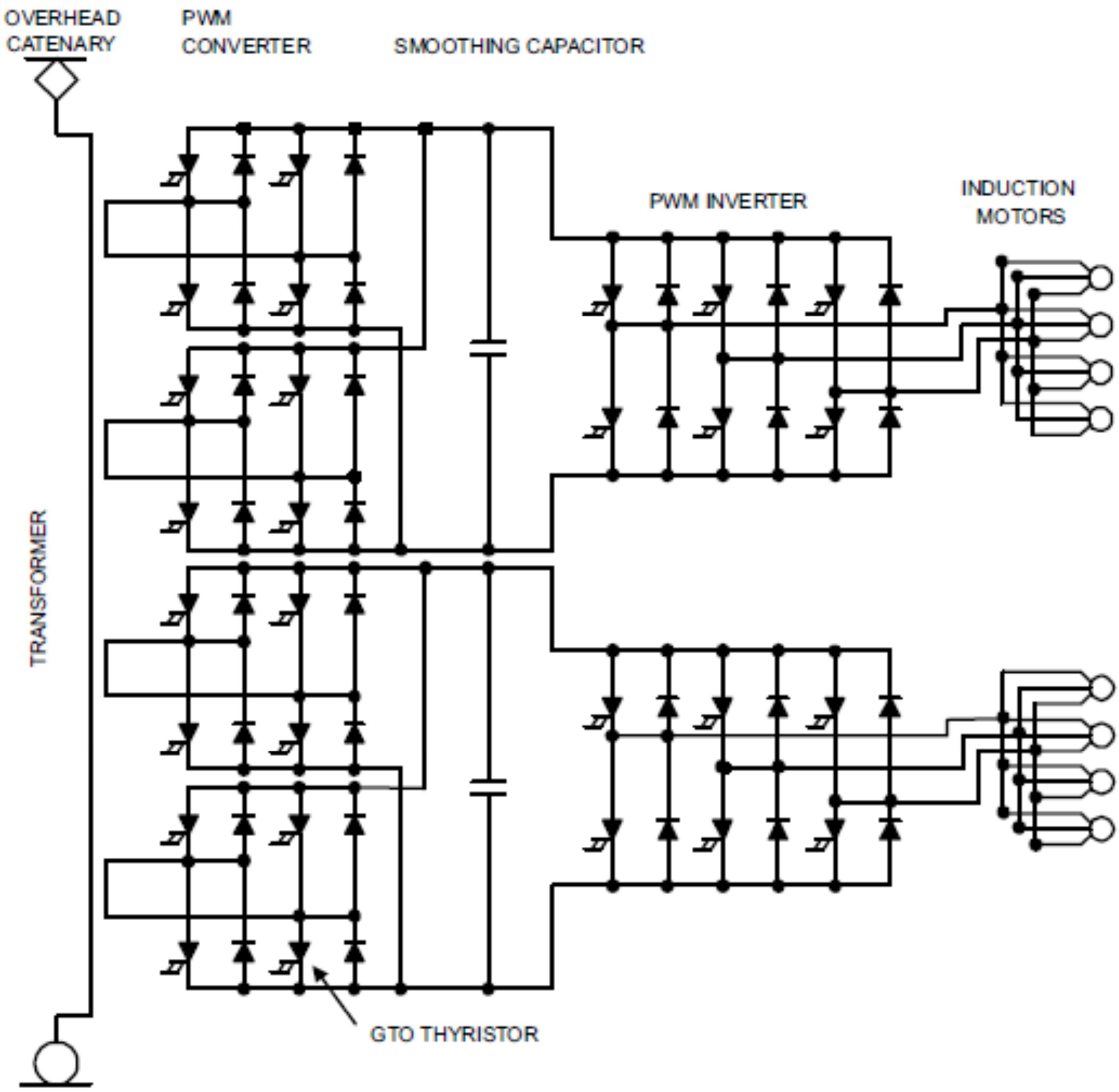


Figure 7: Circuit diagram of 300 series Shinkansen locomotives[37]

[36] (PWM Regenerative Rectifiers: State of the Art)
[37] Locomotives [(PWM Regenerative Rectifiers: State of the Art)

3.2.2 Medium Frequency Traction DC- DC Converters

In general DC-DC (direct current-direct current) converters used in traction are only known as four-quadrant converters (4QCs). However, with 4 QCs and MF (DC/DC) converters it is possible to replace the conventional main transformer by connecting submodules in series. The medium frequency transformer converter consists in two-part core in addition to a primary winding and a divided secondary winding, a first and a second part of the divided secondary winding being configured on a respective side of the primary winding.[38]

Each winding preferably consists of a bundle of moulded hollow-cored conductors that are insulated in common and are traversed by a liquid coolant. With multilevel topology permits the connection to the high voltage catenary. A suitably chosen DC link voltage avoids the oversizing of power semiconductors and provides redundancy. Through is dual active bridge it is possible to obtain the bidirectional power flow. The transfer of pulsating power works as a harmonic absorber on the motor side increases the cooling and reduces the control effort of power flow and voltage.[39]

One of the main concerns is the construction of lighter weight vehicles, the main goal of this topology is to increase the frequency and reduce the transformer weight/size, improving the efficiency of the railway vehicle, this technology is a plus especially in countries with the system 15 kV railway power supply and frequency of 16,7 Hz since the traditional transformers used in the railway vehicles have larger and heavy transformers.[40]

Comparing a conventional traction transformer with the (DC/DC) converters it is necessary to implement the redundancy of subsystems, reducing the reliability of power semiconductors and also the use of special high voltage semiconductors as IGBTs feature a lifetime reduction.[41]

Currently the use of this converter in systems 25 kV railway power supply and frequency of 50 Hz does not show many significant advantages since it is necessary higher insulation requirements for the MF (DC/DC) converter, resulting in a higher weight/dimensions and costs. The conventional 25 kV/50 Hz transformer have minor costs, is smaller and has less weight than the 15 kV/16,7 Hz due to the higher frequency.[42]

The following figure shows a medium frequency (DC-DC) converter for 15 kV/16,7 Hz used in traction vehicles.

[38] (MEDIUM FREQUENCY TRANSFORMER, 30.05.2002) (Electric AC High Speed Services, 2010)
[39] (Ibid.)
[40] (Ibid.)
[41] (Ibid.)
[42] (Ibid.)

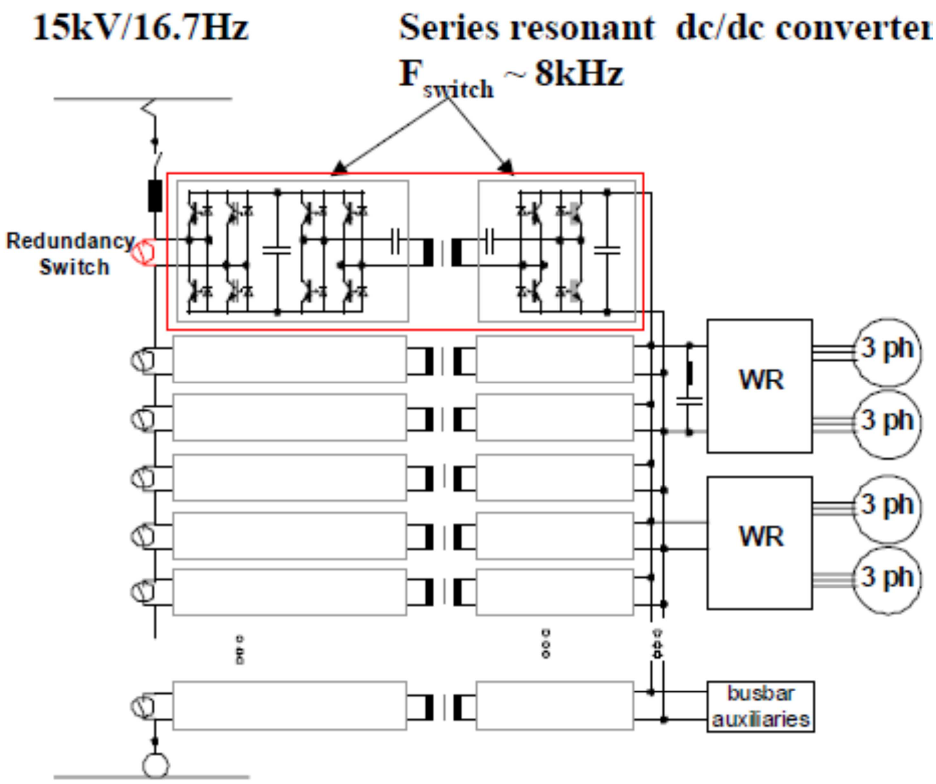


Figure 8: Medium-frequency traction transformer[43]

3.2.3 Semiconductor Devices

The aim of this subchapter is to analyze the main characteristics of typical semiconductors used in railway power electronics circuits.

The selection of components in power electronics circuits requires some care due to specific characteristics circuits design and also the application type.

Nowadays there are three valid varieties of semiconductor that feed variable speed asynchronous or synchronous traction motors. The GTOs (Gate Turn-Off) is the most used semiconductor for high voltages and power. On the market exist GTOs up to a rated switch power of 36 MVA (6000V, 6000A). The disadvantage of the GTO appears to be on the turn-off process caused by the turn-off current, it limits the turn-off (dv/dt) to 500-1000 (V/µs), the complex gate drive and the high power required to control the GTO requiring in parallel a bulky and expensive snubber.[44]

The considerable advantages of this device on the railway vehicles converters are the high on-state current density, the high blocking voltages, the high off-state (dv/dt) and the possibility to integrate an inverse diode. However there are two semi-conductors with more advantageous characteristics than the GTOs.

[43] (MEDIUM FREQUENCY TRANSFORMER, 30.05.2002) (Electric AC High Speed Services, 2010)
[44] (Ramos, 2011) (Recent Developments of High Power Converters, 2000)

The first alternative is IGBTs (Insulated Gate Bipolar Transistor) with higher switching frequencies, these frequencies reduces the current required and therefore the heat generated, giving smaller and lighter units and increasing the efficiency of the converter with lower costs in comparison with GTOs. The high switching frequencies are smoothed on the acceleration process reducing the traction noise that is also an advantage.[45]

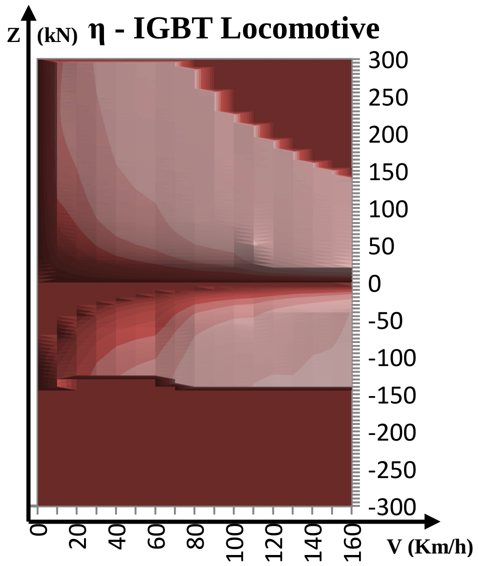


Figure 9: Efficiency degree diagram, IGBTs technology[46]

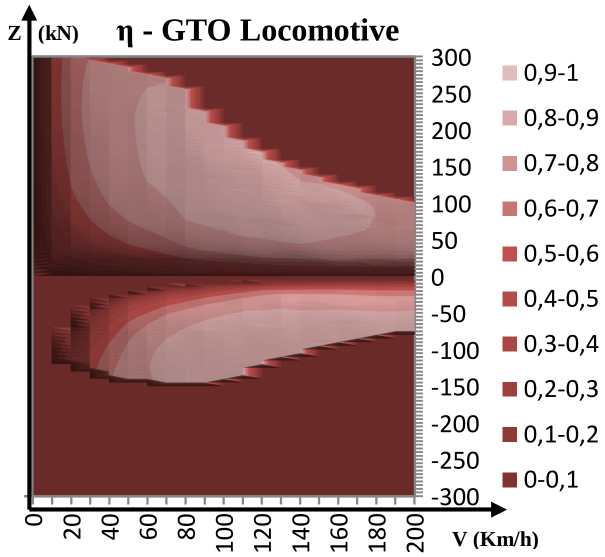


Figure 10: Efficiency degree diagram, GTOs technology[47]

A comparison from both technologies was made by the source[48], between two similar locomotives with average values of efficiency, for the GTO-Locomotive, $\eta_{average}$ = 0,6992 (figure 10), and for the IGBT-Locomotive, $\eta_{average}$ =0,7488 (figure 9). The difference between technologies indicates higher efficiency levels in each degree, being even more uniform in the acceleration and also in the regenerative braking (negative values) with the IGBT technology. This efficiency improvement results in 7,105%, using the IGBTs technology.

The second alternative is IGCTs (Integrated Gate Commutated Thyristor) semi-conductors. The IGCT is a technological improvement of the GTO structure with the inverse diode and a low induction gate drive.

In comparison with IGBT the IGCT offers higher reliability and lower losses at small active silicon area due to substantially smaller on-state voltages improving the efficiency of the converter with lower cost, being the reliability is higher with lower risk of damage and explosion.[49]

[45] (Recent Developments of High Power Converters, 2000)] (VENÂNCIO)
[46] (Ramos, 2011)
[47] (Ibid.)
[48] (Ibid.)
[49] (S. Bernet, 1998)

The IGCT also offers a wide range of the switch power f_s=500 Hz improving the inverter output frequency with an average value of f_o=1000 Hz. Although, the IGBT offers an active control of (dv/dt) and (di/dt), being also possible to reach higher frequencies if an external control acts on the turn-on (di/dt), active clamping, short-circuit limitation, and active protection.[50]

The following figure shows the main power range of semiconductors available on the market.

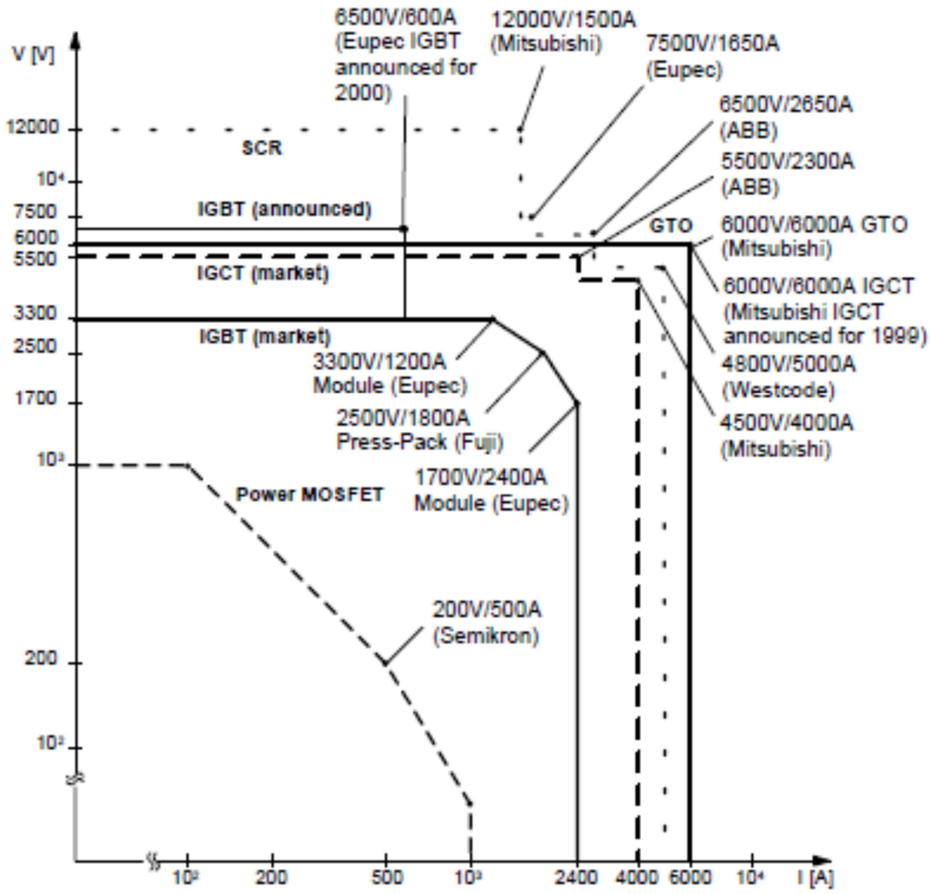


Figure 11: Power range of semiconductors[51]

3.3 Thermal Influence in Traction

One of the main concerns is the thermal influence in the electric equipment of the railway vehicles. The thermal influence causes losses in the transformers, motors, power electronics and transmissions and will affect the efficiency of the locomotive.

The following table estimates the thermal losses in an electric locomotive. As can be seen the major influence of thermal losses occurs in the traction motor.

[50] (Ramos, 2011)
[51] (Recent Developments of High Power Converters, 2000)

Equipment / Thermal Losses	Transformer	Auxiliary Consumption	Power Electronics	Motor	Trans-mission
82 - 87 %	2 - 3 %	2 - 3 %	0 - 1 %	2 - 10%	1 - 2%

Table 3: Influence of the thermal losses in an electric locomotive[52]

3.3.1 Thermal Influence in a Transformer

The transformer efficiency is related with the technical losses; nowadays the state of the art is in the material field; the main goal is to increase the lifetime of the transformer, which requires the use of high quality materials and the introduction of new technology in the manufacture of the equipment, resulting in a price increasing. The useful lifetime loss of the transformer it is established from point of view of the thermal profile. Usually the critical point occurs when the transformer works in overload, increasing the temperature and causing deterioration on the isolation. The heating of the transformer is due to the losses in the copper since the iron losses are proportional to the applied voltage and considered steady. The main factors of concern of the manufacturers are the winding hottest point temperature, the average temperature increase above the ambient air temperature, the ratio between the load losses and no-load (operation) losses and the time constant that operates in overload.

Thought the development and maturity of the MF (DC/DC) converter, the thermal losses will be lower, since the MF (DC/DC) converter needs minor core and iron.[53]

3.3.2 Thermal Influence in a Transmission

Nowadays, transmissions (gears) used in railway vehicles are mechanical. The aim of the gear is to transmit the produced torque by traction motor to the wheels.

Since the thermal process affects the transmissions the major dependency is related to friction that could affect the transfer power. The main concerns to reduce the losses and increase the efficiency are the point contact radius of the object, the maximum speed, the contact material properties and the lubricator used.

Developments are being made to improve this point and their efficiency with the use of permanent magnets transmissions. The benefits of permanents magnets were referred in the chapter (3.1), having the same principle of behavior.

3.3.3 Thermal Influence in Traction Motors

The most critical part for thermal influence is in the electric motor. Is of utmost importance to predict the temperature rise of the electric motor related to the power in order to increase its lifetime.

[52] (Lehmann, 2006)
[53] (Susa, 2005)

Individual components of the electric motor are built separately and they cannot exceed specific values that affect the thermal isolation and functionalities of the motor components. It is shown in annex 1 a model to predict the overtime temperature behavior of electrical motor. In the annex 1 is also shown the time/temperature for different levels of motor load including overloading. The diagram in the annex 1 describes a monophasic motor, although, this comparison can be done for a triphasic motor due to the similarities presented in the construction.[54]

3.4 Traction Efficiency in Railway Vehicles

As mentioned above, reducing energy consumption and the improvement of the energy efficiency is the main concern in traction vehicles. The efficiency degrees diagrams characterize the ratio of output power and the input power for each operating point of the motor. For each operation point, the efficiency calculation is carried out by measure values depending on the speed and the moment of force per time.

These diagrams are considered in the simulation software in order to estimate the vehicle energy consumption during a specific route.

The following figure shows an example of the motor efficiency values on the Taipei Metro EMU.[55]

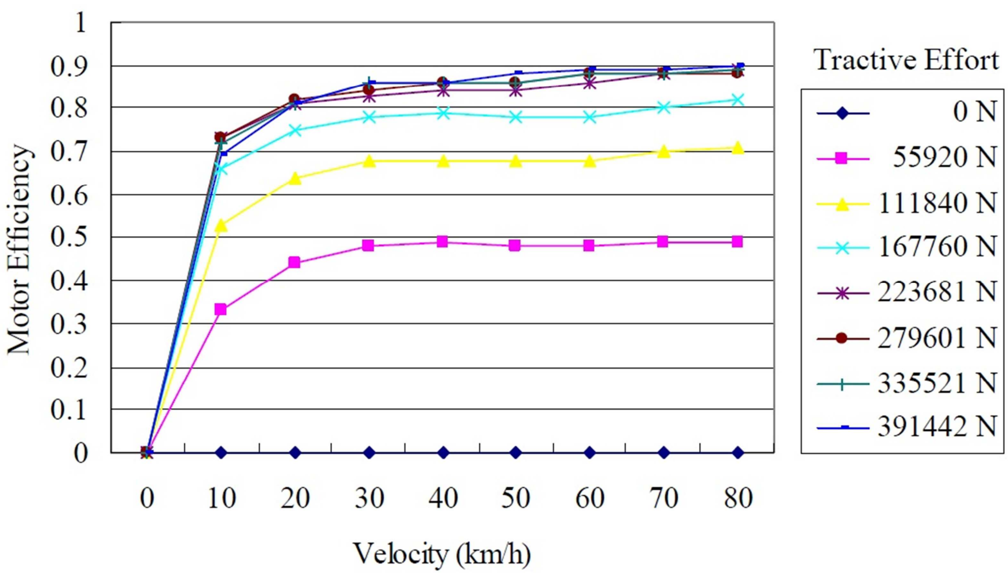


Figure 12: Motor efficiency curves for Taipei metro EMU[56]

Analyzing the figure above the higher efficiency level occurs when the tractive effort and the velocity increases. This offers the possibility to reduce the losses saving energy, although this also depends on the driving strategy, energy storage (in vehicles or off board) and on the timetables (energy/speed tradeoffs).

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54 (Lehmann, 2006)] (USING THERMAL LIMIT CURVES TO DEFINE THERMAL ,2001)
55 (Metro EMU, MODELS FOR ESTIMATING ENERGY CONSUMPTION OF ELECTRIC TRAINS, 2005)
56 (Ibid.)

The quantity of power units it is also important, normally locomotives have only one power unit, meaning, its failure causes the locomotive deactivation unlike the multiple unit, making it more reliable.

3.5 Regenerative Braking of Electrical Vehicles

In the electric railway systems the power consumption of a railway vehicle uses the catenaries or the third/four rail as feeding systems. [57]

Nowadays the electrical railway vehicles uses two different braking systems, usually they are equipped with regenerative braking with anti-lock braking system, since the motor is reversible and it also can work as a generator part of the energy consumption can be recovered during the braking period. The electric power is generated by the kinetic energy of the train and returned to the electrical network system for further use by other trains or is returned to the supplier.

The utility of the anti-lock braking system prevents the limiting factor of adhesion, if there is not enough adhesion, the wheels will lock and slide along the rails, resulting in wheel flats.[58]

The other type of braking system is called electrical braking system where generated energy is converted into heat in some form of resistance carried by the vehicle, and thereby dissipated. Another advantage in the use of regenerative brakes is the lowered wear from the pneumatic brakes prolonging the maintenance intervals. Although the main limitations of full usage of regenerating electric brakes are related with the difficulty of speed detection at a low speed, as a consequence the electric braking are substituted by mechanical braking at a very low speed period. It also happens at a high speed due to the sufficient braking force that cannot be produced according to the field-weakening. However exists control techniques to minimize these limitations such as: independent control systems (mechanic and electric brakes), higher precise converters, the use of dual-rates sampling digital observers, higher electric braking power, systems techniques as ERTMS (European railway traffic management system) including ETCS (European Train Control System) which gives real-time updates for the train dispatcher and the drivers to prevent the braking force.[59]

The extended timetables also provides more opportunities to coast and the regenerative brakes can be used more often with higher results. Although for safety reason the mechanical brakes must be capable to stop the train running at full speed at a minimum distance “emergency brake”.[60]

[57] The study of the third/four rail system will not be included in this thesis
[58] (Eco-driving and use of regenerative electric brakes for the Green Train)
[59] (Braking Systems, 1999)
[60] (Ibid.)

4 Energy Consumption Calculation

The aim of this chapter is to present calculation methods for the energy consumption of the railway vehicles.

Power requirements and running times of vehicles are the major concern for all the stakeholders due to the infrastructure costs and to the energy production for railway vehicles operation. During a railway vehicle operation the calculation of the energy consumption is the starting point to establish the power requirements of a railway line in an efficient way.

The calculation method is designed especially for simulating a simplified transport pattern, which is divided into several elements. This calculus it is not only important for planning the energy consumption during a certain time period but it is also to optimize the time schedule during a path with different types of driving modes in order to save energy.[61]

4.1 Energy Consumption for Electric Traction Vehicles

The total energy consumption can be calculated based on the knowledge of driving resistances and the energy consumption can be calculated through integrating the instantaneous force over the traveled distance:[62]

$$E = \int_{X_1}^{X_2} F_{total}\, dx \tag{4.1}$$

F_{total}: Sum of the driving resistances [N];

E: Energy consumption in the wheel [J];

x: Path distance [m];

The electrical power, P_e can be calculated as:

$$P_e = v.F.\frac{1}{\eta} \tag{4.2}$$

P_e: Electrical power in [W]

v: Speed in [m/s]

F_{tot}: Sum of the driving resistances [N]

η: Efficiency

[61] (MODELS FOR ESTIMATING ENERGY CONSUMPTION OF ELECTRIC TRAINS, 2005)

[62] (Ermittlung des ZV und Züg Diagramms- Prof Dieter Bögle)

With equation (4.1) and (4.2) the energy consumption can be calculated during an elapsed time as:[63]

$$E = \int_{t_0}^{t_1} P_e \, dt \tag{4.3}$$

E: Energy consumption in the wheel [J]

P_e: Electrical power in [W]

t: Path elapsed time [s]

4.2 Driving Resistances Calculation

As stated in the previous subchapter (4.1), to calculate the energy consumption is necessary to identify and calculate the existent resistance forces in the vehicle movement. They can be divided into four main categories such as: mechanical, aerodynamic, grade and inertia resistances. These categories will be described during the following subchapters.

4.2.1 Mechanical Resistances

Due to the mechanical energy dissipation in the vehicle, the mechanical resistances (W_b) are some of the categories that will oppose the vehicle resistances.

The mechanical resistance includes the rolling resistance (W_r), bearing friction (W_{La}) and transmission friction (W_{St}), which will affect the consumption of energy during the vehicle driving and it is variable with the axle weight.

The mechanical resistances (W_b) calculation is the sum of the rolling resistance (W_r), bearing friction (W_{La}) and transmission friction (W_{St}) along the track[64]:

$$W_b[\mathrm{N}] = W_r + W_{La} + W_{St} \tag{4.4}$$

Where the rolling resistance (W_r) is dependent of the vehicle weight and the rolling coefficient for different types of wells and tracks:

$$\mathrm{W_r[N]} = \mu_\mathrm{r} \cdot \mathrm{m} \cdot \mathrm{g} \tag{4.5}$$

m: Vehicle mass [kg];

g: 9,81 [m/s^2];

---

[63] (Ermittlung des ZV und Züg Diagramms- Prof Dieter Bögle)

[64] (Ibid.)

The rolling factor value (μr) depends on the type of wheel used in the vehicle and it is given by table 4:

Type of Wheel	Steel	Pneumatic	Pneumatic on a slippery track	Pneumatic used in Erdweg track
μ_r	0,001	0,007 – 0,015	0,01 – 0,015	0,04 – 0,08

Table 4: Values of the rolling factor (μ_r) [65]

The bearing friction (W_{La}) factor is calculated through the equation (4.6), also depends on the weight of the vehicle and the wheels on the rails, given the bearing friction of the shaft.[66]

$$W_{La}[N] = c_{La} \cdot m \cdot g \tag{4.6}$$

Where the used value of the bearing friction coefficient (C_{la}) is:

m: Vehicle mass [kg] — $c_{La}: 0,4.10^{-3}$: Used in rolling bearing

g: 9,81 [m/s^2] — $c_{La}: 0,9.10^{-3}$: Used in sliding bearing

The transmission friction (W_{St}) factor is calculated through the equation (4.7), besides the weight of the vehicle, it also depends on: the friction between friction springs, shock absorbers, friction-buffers, flanged friction in the straight, rail joints and rail discontinuities.[67]

$$W_{St}[N] = c_{St} \cdot m \cdot g \tag{4.7}$$

Where:

m: Vehicle mass [kg]

g: 9,81 [m/s^2]

$c_{St}: 0,1.10^{-3}$

The mechanical resistances (W_b) can also be calculated including a different factor depending on the railway vehicle type, and is given by the equation (4.8).[68]

$$W_b[N] = c_b \cdot m \cdot g \tag{4.8}$$

65 (Ermittlung des ZV und Züg Diagramms- Prof Dieter Bögle)
66 (Ibid.)
67 (Ibid.)
68 (Ibid.)

Where:

m: Vehicle mass [kg]

g: 9,81 [m/s^2]

c_b : Is given by the table 5

Type of Vehicle	Railway car with rolling-element bearing	Railway car with plain bearing	Locomotive boogie with rolling-element bearing	Driven wheel sets locomotive with axle-hung drives	Driven wheel sets locomotive with hollow-shaft drives
C_b	$1,5.10^{-3}$	2.10^{-3}	$1,7.10^{-3}$	$4,5.10^{-3}$	$5,1.10^{-3}$

Table 5: Values of the mechanical resistance factor (C_b)[69]

4.2.2 Aerodynamic Resistances

The aerodynamic resistance i.e., the air resistance is present mainly in the front side of the train, acting by friction along the sidewalls of the train and by suction the rear of the vehicle.[70]

This resistance is sensitive to several factors such as: the front shape of the vehicle, the range between vehicles and protrusions in the structure.

The aerodynamic resistance can be calculated with the equation (4.9), which uses the equivalent area concept.[71]

$$W_l[N] = \frac{\rho}{2}.(v+v_s)^2.\sum \text{Equivalent area} = \frac{\rho}{2}.(v+v_s)^2.(A'+n.A''+A''') \qquad (4.9)$$

Where:

ρ: Air density [kg/m³]

v: Speed [m/s]

v_s: Speed addition [m/s]

n: Number of wagons wagons

A': Equivalent area of the locomotive [m²]

A'': Equivalent area of the wagons [m²]

A''': Equivalent area of the suction [m²]

There is a certain complexity in the calculation of the A‘‘‘(equivalent area of the suction), although the value of 1,2 m² can be used for a uniform area since the associated error is minimum.

[69] (Widerstände einer Zugfahrt- Prof Dieter Bögle)
[70] (Ibid.)
[71] (Ibid.)

4.2.3 Resistances Calculation through Davis Equation

To calculate the resistances of the subchapters (4.2.1) and (4.2.2) it is also possible to use the *Davis* equation. According to Davis the values of the coefficients A, B and C are given by the following table.

$$R_H\,[\mathrm{N}] = A + B.v + C.v^2 \qquad (4.10)$$

Where:

A : Resistance due to rolling stock and internal friction

$B.v$: Resistance due the energy losses

$C.v^2$: Aerodynamic drag

Vehicle	**A [kN/t]**	**B[kN/(km/h)/t]**	**C [kN/(km/h)^2/t]**
Locomotive	$6{,}37432.10^{-3}$+(0,12896/m)	$91{,}39718.10^{-6}$	$44{,}71883.\ 10^{-6}$.S/(n.m)
Car	$6{,}37432.10^{-3}$+(0,12896/m)	$91{,}39718.10^{-6}$	$6{,}33510.\ 10^{-6}$.S/(n.m)
Freight car	$6{,}37432.10^{-3}$+(0,12896/m)	$137{,}78343.10^{-6}$	$9{,}26728.10^{-6}$.S/(n.m)
Motor car	$6{,}37432.10^{-3}$+(0,12896/m)	$274{,}58620.10^{-6}$	$44{,}71883.\ 10^{-6}$.S/(n.m)
Leading trailer car	$6{,}37432.10^{-3}$+(0,12896/m)	$137{,}78343.\ 10^{-6}$	$6{,}32530.\ 10^{-6}$.S/(n.m)
Secondary trailer car	$6{,}37432.10^{-3}$+(0,12896/m)	$137{,}78343.\ 10^{-6}$	$44{,}71883.\ 10^{-6}$.S/(n.m)

Table 6: A, B, C coefficients of Davis formulas[72]

Where:

m: Vehicle average mass per axle

n: Number of axles on a vehicle

S: Cross-sectional area on a vehicle

As can be seen in the above table the coefficients A, B and C are not constants. The *Davis* equation gives satisfactory results but only for older vehicles.

4.2.4 Gradient Resistances

In normal operation the conditions may be somewhat different. Gradients give rise to extra resistance due to gravitational attraction for a vehicle with mass (m) and angle (α). The following figure shows the applied forces in a moving train.

[72] (Pires, 2006)

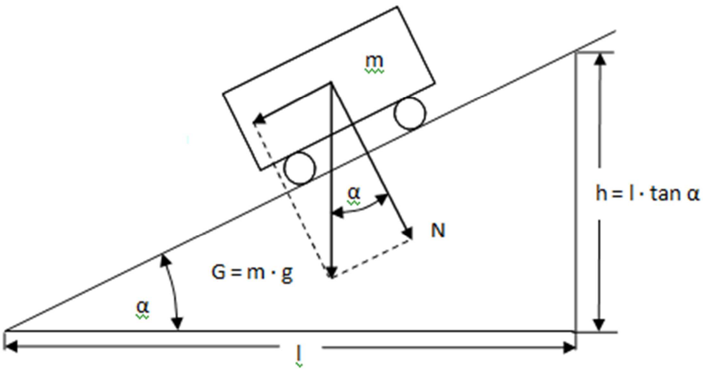


Figure 13: Applied forces in a moving train[73]

The gradient resistance is dependent on the weight of the train and the size of the gradient to which the train is exposed. The calculation of the total gradient resistance is given by the following equation.

$$W_s[N] = m.g.\sin\alpha = m.g.\frac{h}{l}.1000 \tag{4.11}$$

Where:

m: The train mass in [kg]

g: The acceleration of gravity 9,81[m/s^2]

α: The angle of the gradient

h the height difference [m] over the horizontal distance l [m]

4.2.5 Curve Resistances

In a normal operation the curves also influence in the vehicle consumption. The following figure shows the applied forces in curve in the train movement.

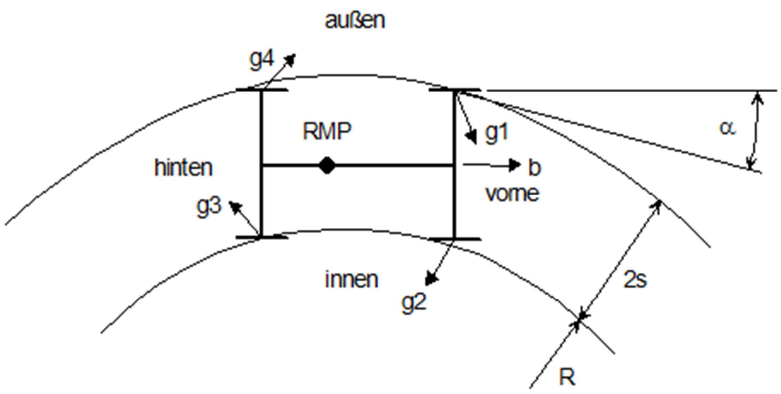


Figure 14: Curve applied forces in a moving train[74]

73 (Widerstände einer Zugfahrt- Prof Dieter Bögle)

74 (Ibid.)

This resisting force is produced by three factors: solidarity wheels and axles, parallel axis and centrifugal force. When the vehicle makes a turn (curve), there are two distinct factors along the movement:[75]

- Due to the solidary and parallelism of the wheels, there is a slip in the outer wheel. It is as if there was a slip circular movement in the wheels at the same time as the inner wheel remain stopped.

- Due to the axels parallelism, there is a sliding of the bogie in a circular motion around his mass center.

Where the curve resistor can be calculated by the equation (4.12) and (4.13), and it is dependent of the curve radius.[76]

When the radius curvature is lower the curve resistor can be calculated by the following equation:

- Sideways Running

$$R < \frac{a^2}{2.w} \Rightarrow W_K[N] = m \cdot g \cdot \frac{\mu}{2 \cdot R} \cdot \left[\sqrt{\frac{a^2}{4} + R \cdot w + \frac{R^2}{a^2} \cdot w^2 + 4 \cdot s^2} + \sqrt{\frac{a^2}{4} - R \cdot w + \frac{R^2}{a^2} \cdot w^2 + 4 \cdot s^2} \right] \quad (4.12)$$

For higher radius curvature it can be used the following equation:

- Free Wheel

$$R > \frac{a^2}{2.w} \Rightarrow W_K[N] = m \cdot g \cdot \frac{\mu}{2 \cdot R} \cdot \left[\sqrt{a^2 + 4 \cdot s^2} + 2 \cdot s \right] \quad (4.13)$$

Where:

m: The train mass in [kg]

g: The acceleration of gravity 9,81[m/s^2]

μ: Adhesion factor (dry conditions μ = 0,25)

r: Radius of curvature [m]

a: Distance between axels [m]

w: Track play (cross section σ = 0,011 m, for small radius curvatures)

s: Half track gauge (European gauge s = 0,75 m)

[75] (Widerstände einer Zugfahrt- Prof Dieter Bögle)
[76] (Ibid.)

The equation (4.12 and 4.13) does not assume friction between the wheel flange and the flank of the head rail. The factor F includes the friction factor (µ Sp) and the flank angle of the flange (β) is given by the equation (4.14).

$$F = 1 + \mu_{Sp} . \tan\beta \Leftrightarrow W_{KSp}[N] = W_{K.F}[N] = W_K .(1 + \mu_{Sp} . \tan\beta) \qquad (4.14)$$

Where:

μS_p = 0.03 (for dry conditions without flange lubrication)

μS_p = 0.05 and β=70° (for dry conditions with flange lubrication)

4.2.6 Inertia Resistances

When the vehicle with a mass (m) is accelerated (a) through the applied traction force, the moving mass translational and the rotating masses (ρ) of the axles and motors must be considered.

The acceleration resistance calculation is given by the following equation (4.15).[77]

$$W_a\,[N] = m \cdot (1 + \rho) \cdot a \qquad (4.15)$$

Where the rotating masses ρ value is different for each type of vehicle, this value is given by the following table:

Vehicle	ρ
Freight car	0,04
Load freight car	0,08…0,1
Electric rail car	0,12
Electric locomotive car (BR 110)	0,135
Electric locomotive car (BR 140)	0,213
Electric locomotive car (BR 141)	0,205
Electric locomotive car (BR 150)	0,24
Electric locomotive car (BR 194)	0,25
Electric locomotive car (BR 120)	0,12
Coaches	0,05…0,06
Car	0,15 to 0,18
Cogwheel locomotive	1,81

Table 7: Value of vehicles rotating masses (ρ)[78]

[77] (Widerstände einer Zugfahrt- Prof .Dieter Bögle)
[78] (Ibid.)

Using the equation (4.15), the negative acceleration is given by the equation (4.16):

$$W_b + W_l + W_a = 0 \Leftrightarrow a[m/s^2] = -\frac{W_b + W_l}{(1+\delta).m} \tag{4.16}$$

The time of braking (t) and the distance braking (s) is given by equations (4.17) and (4.18):

$$t[s] = \frac{v}{a} \tag{4.17}$$

$$s\,[m] = \frac{v^2}{2.a} \tag{4.18}$$

4.3 Energy Consumption of Auxiliary Systems

The modern passenger railway vehicle provides a number of on-board services, both for passengers and control systems. They are almost all electrically powered, although some require compressed air for few vehicles uses hydraulic fluid. Since the train is virtually a self-contained unit, all the services are powered and used on board.[79] In addition, comfort service for the passenger and the crew compartments uses energy for heating, ventilation, air condition, lighting, food preparation, information system, doors, toilets, car body tilt etc.[80]

The auxiliary power supply system is generated either by the auxiliary converters or feed from the external three-phase inlet connection via pantograph. There is one auxiliary converter in each railway vehicle and they are connected to a three-phase bus. The three-phase supply voltage to the auxiliary converter is taken from the DC-link in the auxiliary converter and it converts the DC voltage to a three-phase voltage. Also use a filter that reduces the electric harmonics from the converter output and a transformer that isolates the high voltage converter output. If one converter fails, the output will be reduced.[81]

Normally in driving simulation tools the energy consumption rate of the auxiliary equipments is considered as a constant during the time. Since it is not possible to acknowledge the exact value of the auxiliaries' equipment consumption due to the factors which impact on energy consumption such as resistances and power needed for passenger comfort, heating and air-conditioning during seasonal times.[82]

Although in this point the following assumptions will be made on the auxiliary consumption, there will be variations during the operation time and also during seasonal time. The average values of auxiliary consumption for locomotives and railway coach will be considered.

[79] (Piotr Lukaszewicz, 2009), (MODELS FOR ESTIMATING ENERGY CONSUMPTION OF ELECTRIC TRAINS, 2005)
[80] (Ibid.)
[81] (Ibid.)
[82] (Ibid.)

It is also presented in this point a comparison between auxiliary's consumptions in Germany and in Portugal. Estimations values of seasonal temperatures are as well considered in this comparison.

In the table 8 is calculated the average values of temperature during seasonal time between the capital cities of Portugal (Lisbon) and Germany (Berlin).[83]

Season / Country	**Winter (Nov-Feb)**	**Summer (Jun-Sep)**	**Transition time (Mar-Mai and Oct)**	**Low Temperature**	**High Temperature**
Germany	1 °C	16,25 °C	8 °C	-23 °C	35 °C
Portugal	11,25 °C	21,25 °C	15 °C	-1 °C	42 °C

Table 8: Average values of temperature between Portugal and Germany[84]

The table 9, shows general values used in auxiliaries consumption of the railway coach during the winter with temperatures of -20 °C and summer with +30 °C.

Railway Coach Auxiliary Equipment	**Coach Energy Consumption [kW]**	
	Winter for -20 °C	**Summer for +30 °C**
Passenger compartment heating	40	-
WC heating	3	-
Domestic hot water heating	1,5	-
Waste water heating	2	-
Ar ventilation	1,5	1
Batteries	3,5	3,5
Climitization cooling	-	16
SUM	51,5	20,5

Table 9: Average values of the railway coach auxiliaries' consumption[85]

Through the values of table 9 and assuming only the batteries consumption 3,5 [kW] for the wellness temperature 20 °C, the figure 15 presents two estimation curves, associated with two trend lines.

[83] (2012)
[84] (Ibid.)
[85] (Bögle)

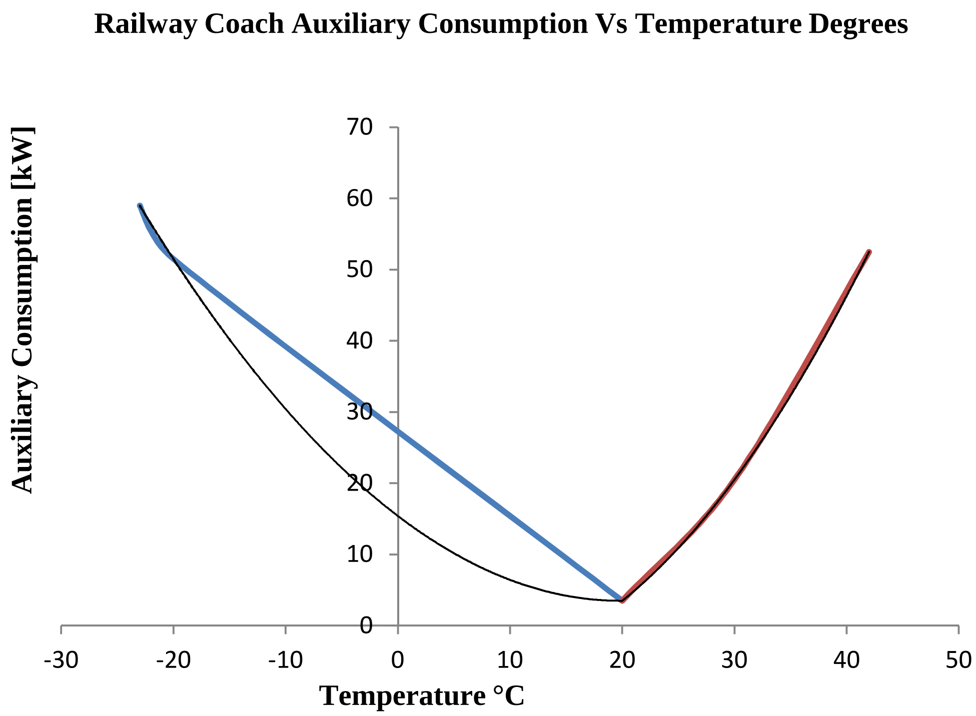


Figure 15: Auxiliary consumption vs. temperature degrees values

Through the table 9 and the interpolation made, the obtain equation is given by:

$$y=0,002.x^3-0,002.x^2-1,9842.x+28,05 \quad (4.19)$$

Where:

y: Auxiliary consumption [kW]

x: Temperature [ºC]

It is presented in table 10 the average values of auxiliary consumption for different railway coach used in Germany and in Portugal.

As can be seen in table 10 the battery system was considered as a constant during all seasonal variation time, since its task is to generate and distribute a 110 V in DC uninterrupted power supply voltage to all battery loads in the train base unit and also to charge the batteries. In addition the battery system function includes the control system, the lightning and the emergency ventilation.[86]

[86] (Bögle)

Railway Coach Auxiliary Equipment / Auxiliary's Consumption	Winter (Nov-Feb)		Summer (Jun-Sep)		Transition time (Mar-Mai and Oct)	
	Germany	Portugal	Germany	Portugal	Germany	Portugal
Passenger compartment heating	9,63	4,00	-	-	5,22	2,85
WC heating	0,72	0,30	-	-	0,39	0,21
Domestic hot water heating	0,36	0,15	-	-	0,20	0,11
Waste water heating	0,48	0,20	-	-	0,26	0,14
Ar ventilation	0,36	0,15	0,07	0,08	0,20	0,11
Batteries	3,50	3,50	3,50	3,50	3,50	3,50
Climitization cooling	-		1,06	1,30	2,09	1,14
SUM [MW]	15,1	8,3	4,6	4,9	11,9	8,1

Table 10: Railway coach auxiliaries' consumption in Germany and Portugal[87]

The figure 16 gives the percentage of the maximal railway coach auxiliaries' consumption used during seasonal variation times. Analyzing the summer percentage used in both countries it can be seen that the value is similar. The author proposes a detail study during transition seasons with the introduction of more measured values in order to improve the curve of the figure 15 and obtain a more realistic equation. Compared with the actual values, this curve can be considered as a valid approximation.

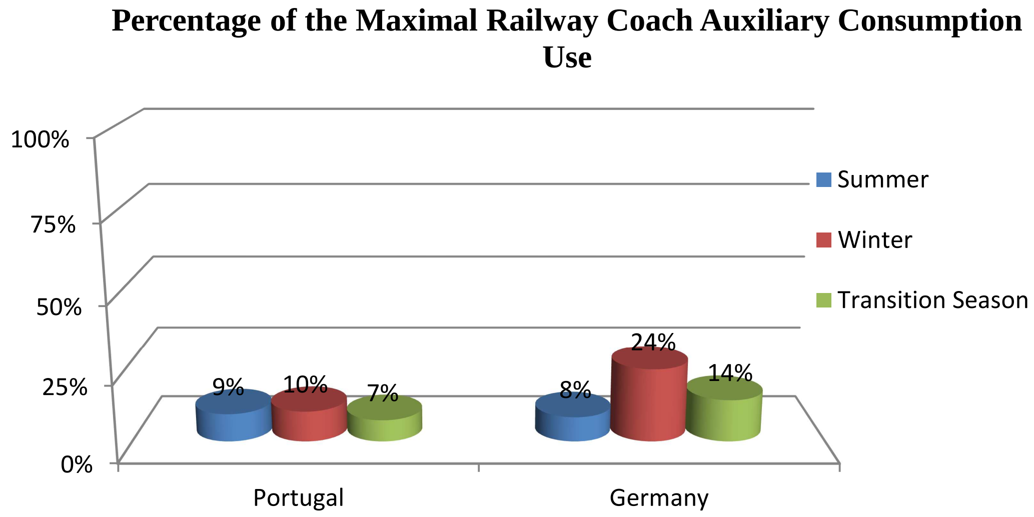


Figure 16: Percentage of the maximal railway coach auxiliary consumption use

[87] (Bögle)

The energy consumption of auxiliary systems for three different types of railway vehicles is calculated in the Table 11. The percentage value used in the (figure 16) is considered during seasonal transitions times.

Type of Vehicle / **Consumption**	**ET 425-Electric Regional Train**		**BR 145-Electric Locomotive**		**IEC 3-High Speed Train**	
	Germany	Portugal	Germany	Portugal	Germany	Portugal
Nominal power [kVA]	280	280	900	900	1000	1000
Heating power [kW]	176	176	-	-	-	-
Auxiliary converter [kW]	210	210	150	150	750	750
Winter [kW]	92,9	38,6	76,5	27	382,5	135
Summer[kW]	25,5	31,4	11,7	11,7	58,5	58,5
Transition time [kW]	50,4	27,5	37,5	15	187,5	75
Average per year [kW]	56,3	32,5	41,9	17,9	209,5	89,5

Table 11: Consumption of vehicle trains in Germany and Portugal

Through table 10 and table 11 it can be applied the following formula and calculate the auxiliary energy consumption for different seasonal transitions times, during the operation time.[88]

$$E_a = \frac{P_a \times t_a}{3600} = \frac{(P_{am} \times n_m + P_{at} \times n_t) \times t_a}{3600} \qquad (4.19)$$

Where:

E_a: Total energy consumption for auxiliary equipment [kWh]

P_a: Total electric power for auxiliary equipment [kW]

T_a: Train operating time [s]

P_{am}: Electric power per locomotive car [kW]

n_m: Number of locomotive cars

P_{at}: Electric power per railway coach [kW]

n_t: Number of railway coach

[88] (MODELS FOR ESTIMATING ENERGY CONSUMPTION OF ELECTRIC TRAINS, 2005)

5 Traction Power Supply Systems

The main goal of the traction power supply systems is to ensure an uninterrupted, reliable and safe operation of the electric traction vehicles.

Due to historical and political reasons a distinct voltage levels is used in the railways throughout Europe (as well as different levels of frequency AC systems). In the following figure it is possible to analyze the different systems, characterized by its voltage level and frequency used in Europe as well as the interconnection between railway countries.

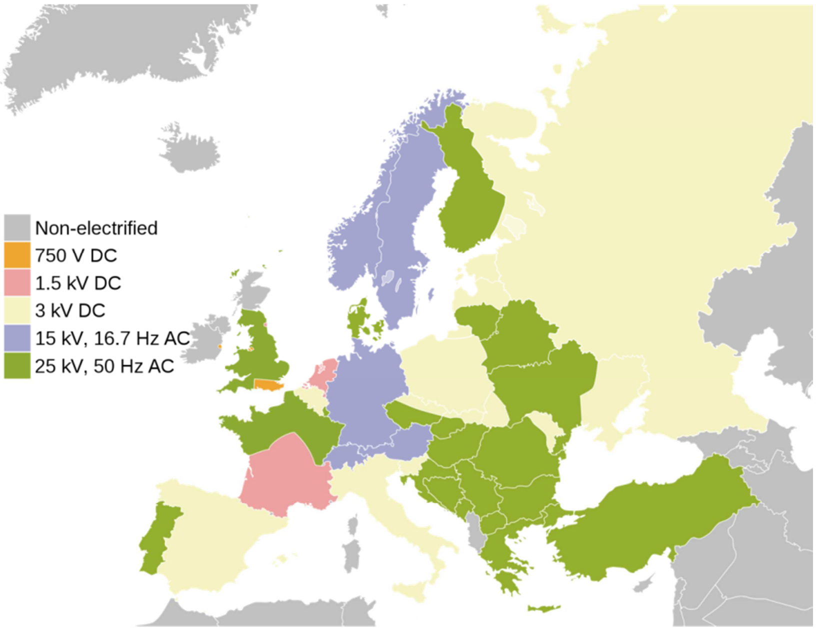


Figure 17: Voltage levels in Europe[89]

The traction power supplies are classified by three main parameters:

- Voltage Level;
- Current (DC and AC 50 Hz / 16,7 Hz);
- Contact Line (Catenary, 3º or 4º Rail);

5.1 Voltage Levels of the Power Supply Systems

The electrical system can be classified in two types such as: direct current or alternating current.

Normally DC system is used in urban areas or metropolitan railway lines with values of voltage, between 600/750 V and 3 kV.

[89] (Wikipedia)

In heavy railway systems the usual voltage levels are 1500 V or 3000 V. The AC systems fulfill the faster sections between cities, having higher levels of the voltage with the magnitude of 15 kV with a frequency of 16,7 Hz; 25 kV with 25 or 50/60 Hz.

The permissible range of voltages that is allowed is given by the standards regulation norms EN 50163 and IEC 60850. Taking into account the number of trains drawing current and their distance from the substation.[90]

The main characteristics of traction power supplies systems in Europe are shown in the annex 2.

5.2 Advantages vs. Disadvantages of alternating and direct current

The major advantage of using alternating current is due to the transport of energy that is carried out at a high voltage in the power substation. This provides a lower current density circulation on the conductors allowing the use of a lower electrical cross section. Being the conductors as well as the support system (catenaries), it is lighter and not so expensive. Since there is a lower intensity of electric current, the *Joule* effect losses and voltage drops are minor, leading to lower quantity of power substations. Due to the advantages mentioned above this system is the best solution for long distances.

Another disadvantage in the DC railway supply system is ground return current since they reach higher values. In the DC system the regulation assumes an installation of a power substation between 8 km to 14 km. In the AC system this range is increased from 30 km to 90 km, which causes minor financial costs.

The major disadvantage when using alternating current is related with the unbalances caused by the injection of negative sequence current in the national electricity network. It is also necessary to install in the locomotives, heavy and expensive transformers to reduce the high voltage into low voltage. The DC system does not require the rectifier on board of the train as it is in the AC system, which makes the train simplest (less equipment on board) and less expensive. In DC system the price of the kWh in medium voltage is more expensive and also requires more substations compared with the AC system, although this system is used in shorter distances, which make the system profitable.

The regenerative recovered with the DC system is sent back to the DC bus, being almost totally utilized. The other trains that usually circulate in the same area take advantage of the energy from the regenerative braking. Although in AC systems the usage of regenerative energy is usually higher due to lower overvoltages.[91]

[90] (Kiessling,2009) (Electric railway traction, 1994) (OPTIMISING AC ELECTRIC RAILWAY POWER FLOWS, 2003)
[91] (Ibid.)

5.3 Central and Decentralized Power Supplies

As it can be seen in the following (figure 18), normally the railway sections are feed by the near electrical power plant. The energy transport is made through the high voltage lines from the electric power plant to the traction power substations along the railway line where the voltage values is reduced to the nominal value and injected separately between the feeding circuits. Normally all the electrical network is interconnected, the several sections of the track are electrically isolated from each other in order to promote one affordable and optimized energy management.[92]

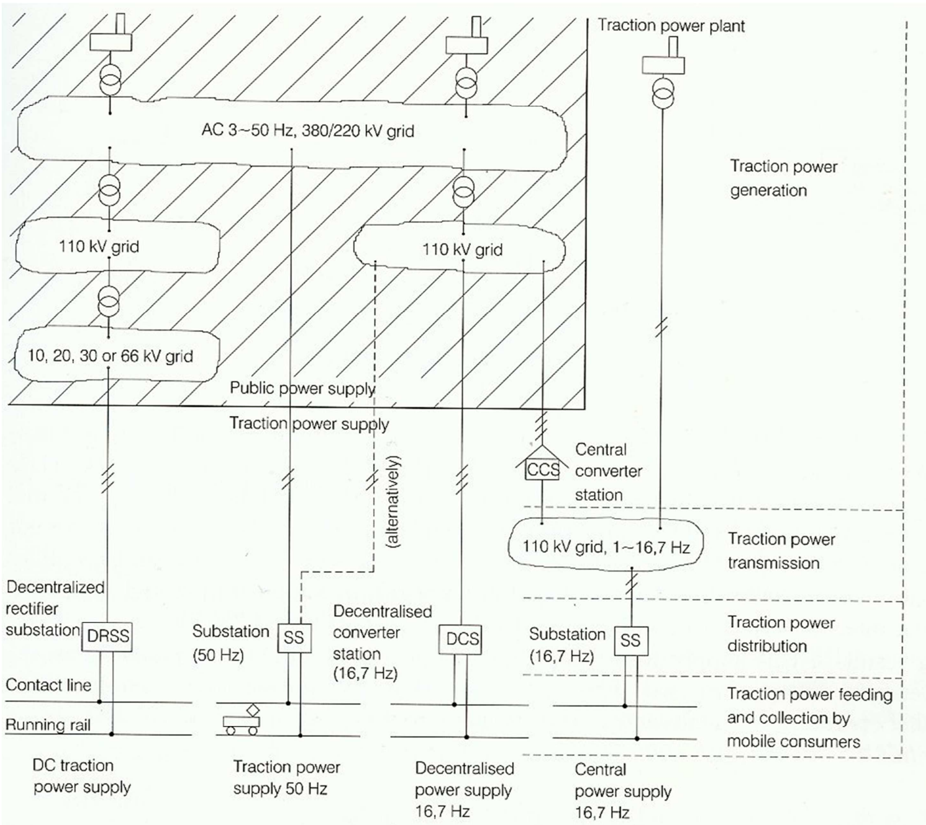


Figure 18: Substation feeding system (16,7 Hz system)[93]

As can be seen in the (figure 17), in the North of Europe some of the railway countries as Germany, use two different feeding systems: the central system which provides their own railway power plants (figure 18), using the special frequency of 16,7 Hz in the energy generation with two circuits and single-phase generators and the decentralised system. The major advantage of using this special frequency is the possibility to obtain the same value of power in 1/3 of the time and also it has lower inductive losses in comparison with standard frequencies. The transmission and the distribution of the electric system has the same function as the decentralized system although the frequency remains at 16,7 Hz, but with a single-phase network instead of the three-phase network used in the decentralized system.

[92] (Optimization of Decentralized Energy Supply Systems) (Kiessling, 2009) (Electric railway traction, 1994)

[93] (Ibid.)

In the decentralized system the power plants belong to the utility electric grid with a frequency of 50 Hz and in the traction power distribution it is used DRCS (Decentralized rotating converter station) or DSCS (Decentralized static converter station) in order to transform the frequency to 16,7 Hz. The DRCS uses rotating machines (synchronous-synchronous converters) instead of electronic power components used in the DSCS.

In comparison the central traction power system normally uses a higher short-circuit current around 45 kA, instead of the 25 kA from the decentralized system, this leads to a higher short-circuit power and lower upward impedance.

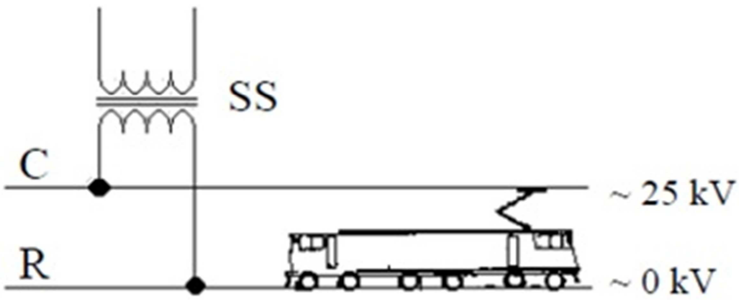
When the short-circuit power is higher the network also has a higher capability of generation and load variations which leads to a robust system. The high cost of the protections, the equipment and also the cables represents a disadvantage.[94]

Another aspect related with the efficiency can be found in the central system. Without the influence of the converter leading to losses reduction, this system is more efficient being the frequency generated with the adequated value.

One of the indicators that affect the efficiency of transmission and generation of electrical grid is the load power factor. When the power factor is low the energy concessionaires will charge by the additional required power in the decentralized system. In the central system the generated energy power required is produced by the same producer which means a lower cost, especially when they have higher peaks of consumption being the generation feasibly adapted to those variations improving the power factor.

5.4 AC Railway Systems

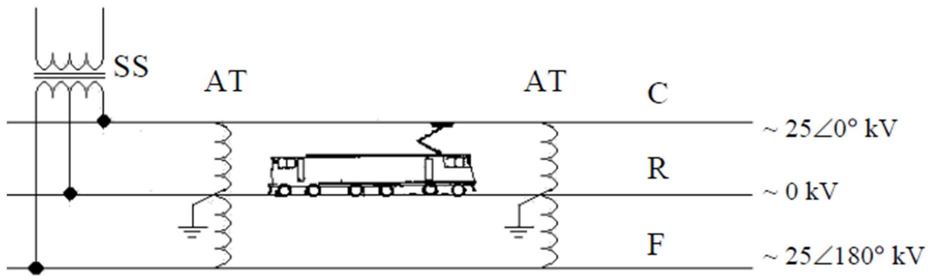
As can be seen in the following figures 19a) and 19 b) , there are two main types of technologies used in the catenaries systems, namely single-phase system and auto-transformer system.



a) Single-Phase AC System[95]

[94] (Optimization of Decentralized Energy Supply Systems), (Kiessling, 2009),(Electric railway traction, 1994)

[95] (Ibid.)



b) Auto-Transformer System (AT)[96]

Label:

- Substation (SS)
- Contact line (C)
- Rail (R)
- Feeder wire (F)
- Return conductor (RC)
- Auto-transformer (AT)

Figure 19: AC railway system

Auto-transformer (AT) system as can be seen on figure 19 b) uses auto-transformers leading the double voltage with the introduction of an additional conductor to catenary and return circuit, the negative feeder. The distribution of AT transformers is sparser between 10 km and 12 km, which enable a longer supply section up to 80 km.

The major advantage of the AT technology compared to the single-phase AC system is in low impedance due to the circulation of the current being made in a lower dimension mesh from the substation to the load, which implies lower power losses. Also the magnetic field produced in the AT system is lower due to the lower distance, which separates the conductors that carry most of the current traction.

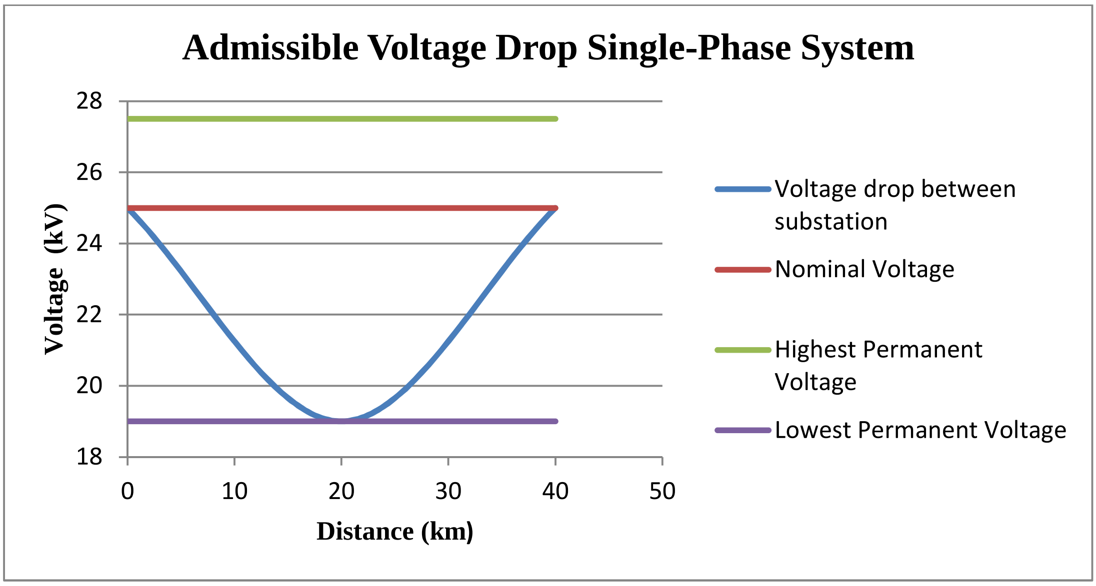
The figure 19 a) shows the single-phase AC system. This installation along the railway line consists in a contact line and the return circuit. The maximum length to be supplied with this system is 40 km due to the tolerable voltages drop. This system presents higher electromagnetic interferences compared with the auto-transformer (AT) system, although this system can also use a double return conductor minimizing the losses and the electromagnetic fields.

This return conductor will also provide an increase in the distances between substation around 40 km and 60 km.

As an advantage with this system, the substation design is simple for only one phase, which reduce the costs. When the load is lower and the interferences do not impose any constraints it is preferred the use of the single-phase AC system, due to its the effective costs.

In the figure 20 is presented the permissible values of voltages drop between two substations for the two different types of power supply systems with uniformly distributed load.[97]

[96] (Optimization of Decentralized Energy Supply Systems), (Kiessling, 2009),(Electric railway traction, 1994)



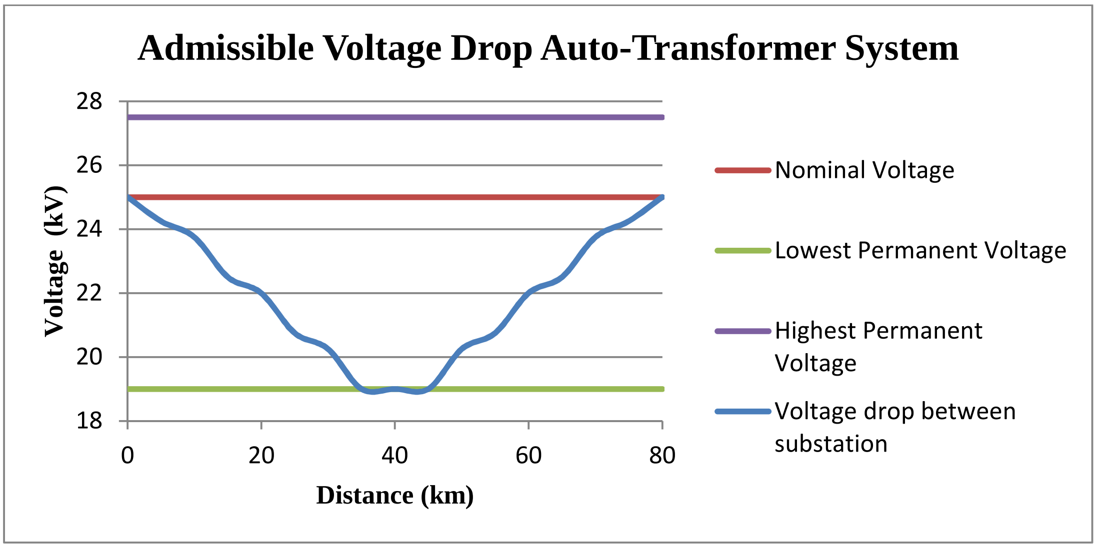


Figure 20: Admissible voltage drop for AC 25 kV 50 Hz system

Analyzing the figure above, due to the minor voltage drop in the AT system, this allows higher distances between substations. The curve behavior in the single-phase system shows a perfect sinusoidal curve since the system does not support the picks of the transformers between substations.

Normally capacitors are installed in the negative feeder to compensate and reduce the current.

The annex 3 presents some variations that can occur and its influences in the traction power system.

[97] (EN 50 163)

5.5 DC Railway Systems

Typically this system converts the high and medium voltage rectified current to the operating level (voltage/current) of the railway system. The major characteristic of this system assumes small distances 4 km and 30 km between substations. Normally is applied in meshed networks. The distribution system in the DC system includes traction substations in order to reduce and convert AC voltage to DC.

The schematic diagram of a DC distribution system is presented in the following figure.

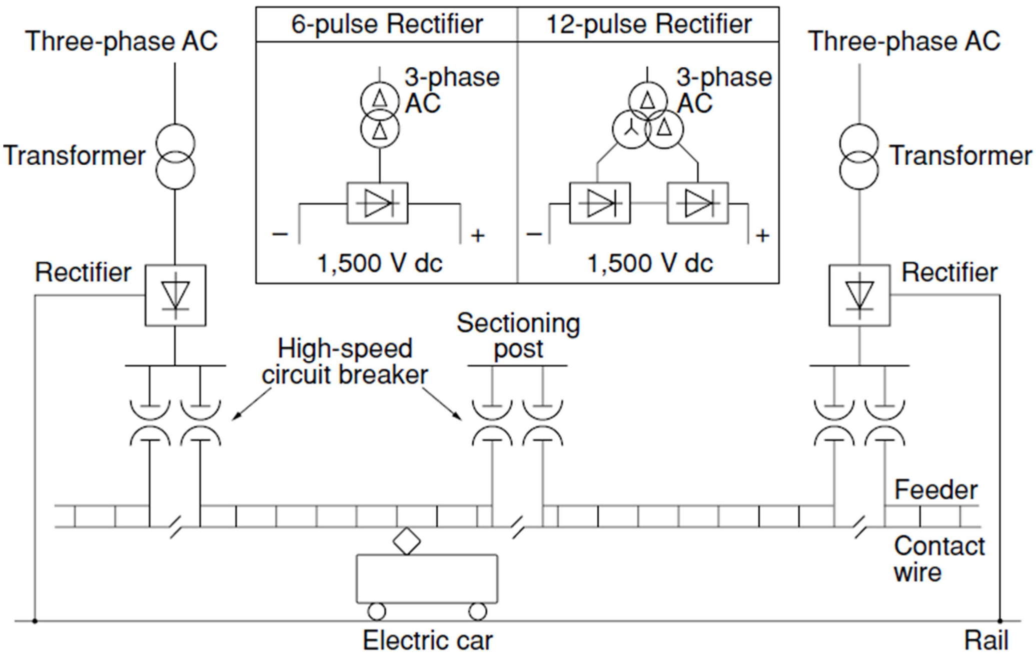


Figure 21: AC / DC schematic of DC power distribution system for railways[98]

The traction power substations AC/DC, can have one or two transformers with the Y / Y / Δ or Δ / Δ / Y winding type connection. Due to the lack of the neutral conductor the most common connection is the Δ / Δ / Y, when feed by the electrical grid. In the transformers output the AC voltage reduction is obtained. The figure 21 shows the output transformer connected with two rectifiers of six pulses or with twelve pulses, with the twelve pulses rectification it is possible to reduce substantially the amount of the harmonic component.[99]

[98] (Railway Electric Power Feeding Systems, 1998)
[99] (Ibid.)

In the table 12 is presented a resume of the advantages that should be taken in consideration in choosing an adequate type of system used in traction:

Type of System	Advantages vs. disadvantages of the used system
DC 1,5 kV - 3 kV	• For the connection with the same type of system, DC system presents advantages, using simple equipment in the vehicles since it is not so complex in quantity, size and weight in comparison with the equipment used in the vehicles of the AC system. • As disadvantages the DC system requires more traction power substations. • This system does not imply imbalances in the public energy network.
AC 25 kV 50 Hz	• With this system the number of traction substations decreases, since the voltage is higher and also the losses decrease due the lower current. • This system is inexpensive due to lesser weight system from the catenaries and also to smaller size conductors compared with DC system. The price of the kWh is not so expensive. This system should be used when is not necessary a higher capability of traffic as the DC can provide. • Compared with the AC 25 kV at 16,7 Hz, is not so expensive since the rectifiers are not necessary in the traction power substation because it is not required the special frequency of 16,7 Hz.
AC 15 kV 16,7 Hz	• For longer distances the kWh is not so expensive in the central system since the railway companies produce their own energy in the special frequency; thereby the rectifiers are not required in the traction power substation. • With the special frequency of 16,7 Hz, the impedance value is lower compared with the AC 25 kV at 50 Hz, reducing the *Joule* effect losses.

Table 12: Resume of the railway systems[100]

[100] (Railway Electric Power Feeding Systems, 1998)

6 Traction Power Supply Stations Models

The main focus in this chapter is the presentation of models that characterize the power supply system in order to develop a calculation method to estimate the power flow in the railway power supply system. As described in the previous chapter the electrical system consists in generation, transmission and energy distribution.

6.1 Models of the Electrical Railway Elements

The constituent elements of this system are modeled by their equivalent impedance. In order to simplify the model only resistances and inductances are considered, this approach reflects the system only for practical applications. In this model the connections to the busbars are carry out through transformers, generating set and lines.

6.1.1 Transformer

The use of the transformer allows voltage variations in the network, it can work as a step-up or step-down voltage level.

It was used in this model the simplified equivalent circuit.[101] The transversal magnetization branch was neglected due to the low magnetization current, only the longitudinal branch was considered as the short-circuit impedance. The simplified model is shown in the following figure.

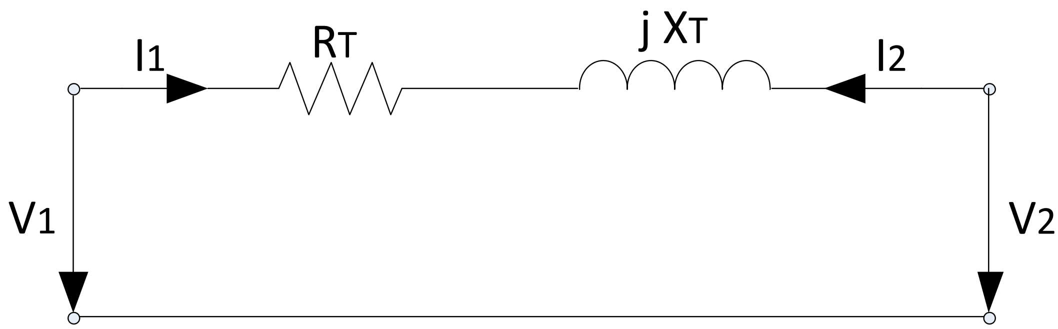


Figure 22: Simplified schematic of the transformer

Since the currents are equal, the relation between the primary and the secondary voltages is given by:[102]

$$V_1 = V_2 + Z_T.I \tag{6.1}$$

The impedance is given by:

$$Z_T = R_T + jX_T \tag{6.2}$$

[101] (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)
[102] (Ibid.)

Through the short-circuit test it is possible to calculate the transformer impedance. In this model the transformer impedance is given in the (p.u.) system and is calculated by the following equation:

$$Z_T(\text{p.u}) = \frac{Z_{TCC}(\Omega)}{Z_b} = \frac{j\left(\frac{V_{cc}}{100}\right).\left(\frac{{V_{2n}}^2}{S_n}\right)}{\frac{V_b^2}{S_b}} \tag{6.3}$$

6.1.2 Transmission Lines

The transmission line provides the energy transport along the feeding system.

The equivalent circuit considers the longitudinal impedance Z_L and the transversal admittance Y_T in a lumped-element. The π equivalent circuit model is shown in the following figure.[103]

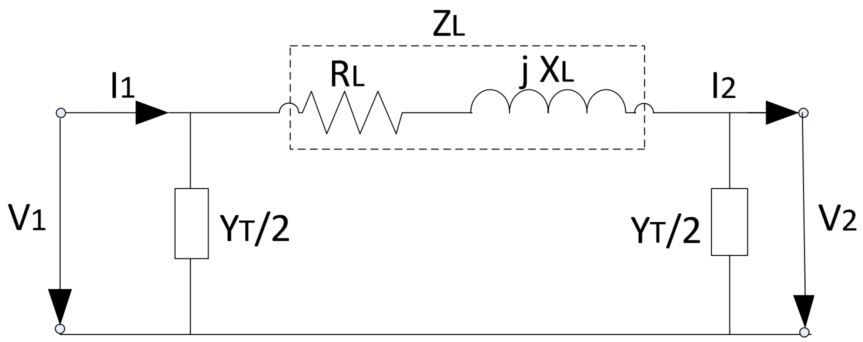


Figure 23: Simplified schematic of the transmission line

The equation of the transmission line is given by:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 1+\frac{Z_L.Y_T}{2} & Y_T \\ Y_T.\left(1+\frac{Z_L.Y_T}{4}\right) & 1+\frac{Z_L.Y_T}{2} \end{bmatrix} . \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{6.4}$$

In order to simplify the model the transversal admittance is not considered. The transmission line equation is given by:

$$V_1 = V_2 + Z_L.I \tag{6.5}$$

The impedance in the (p.u) system is given by:

$$Z_L(\text{p.u}) = \frac{Z_L(\Omega)}{Z_B} = Z_L.\left(\frac{S_b}{V_b^2}\right) \tag{6.6}$$

[103] (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)

6.1.3 Synchronous Machine

The generation set consists in the synchronous machine; this machine ensures the frequency and the voltage along the network. The single-phase model in the stationary steady state is shown in the the following figure.[104]

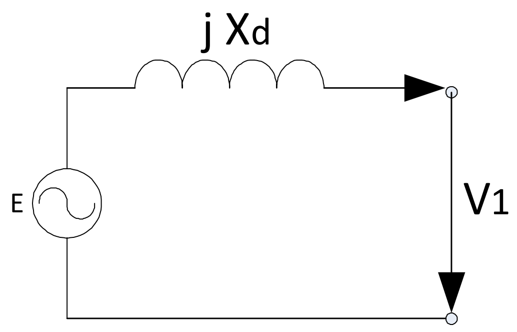


Figure 24: Simplified schematic of the synchronous machine

The synchronous motor electromagnetic force (f.m.e) is given by:

$$U_1 = jX_d.I + E \tag{6.7}$$

The impedance can be calculated in the (p.u.) system:

$$Z_G\,(\text{p.u.}) = \frac{X'_d\,(\Omega)}{Z_b} = \frac{\frac{x'_d\,(\%)}{100}.\frac{V_n^2}{S_n}}{\frac{V_b^2}{S_b}} \tag{6.8}$$

6.1.4 Upstream Network

This model considers the upstream network impedance as the main case study, this impedance can be characterized by the line-to-line short-circuit power impedance.

The simplified schematic of the railway power supply system is shown in the following figure.

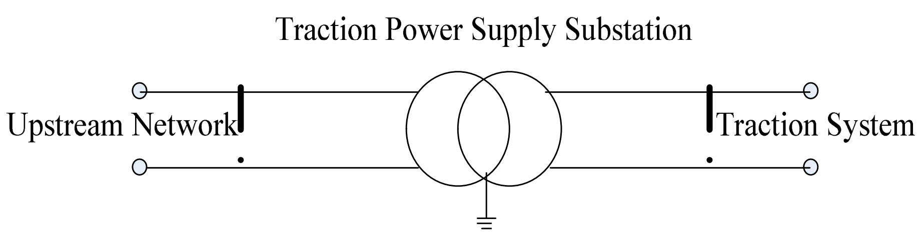


Figure 25: Simplified schematic of the railway power supply system

[104] (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)

The impedance in the (p.u.) system is given by:[105]

$$Z_{\text{Upstream\_network}}\left(\text{p.u.}\right)=\frac{Z_{\text{Upstream\_network}}\left(\Omega\right)}{\text{Z}_{\text{b}}}=\frac{\dfrac{\text{V}_{2n}^{2}}{S_{cc}}}{\text{Z}_{\text{b}}} \tag{6.9}$$

6.1.5 Traction System

The traction system impedance consists in the active conductors for the single-phase system. The single-phase equivalent impedance can be measure with the short-circuit test.

The impedance in the (p.u) system is given by:[106]

$$Z_{\text{Traction\_System}}\left(\text{p.u.}\right)=Z_{\text{Traction\_System}}\left(\Omega\right)=\frac{(\text{R}_{\text{C+R}}+\text{j.}\omega\text{X}_{\text{L}_{\text{C+R}}})}{\text{Z}_{\text{B}}} \tag{6.10}$$

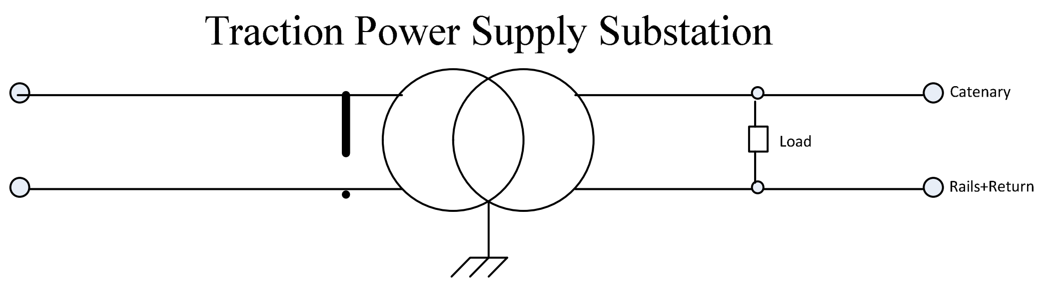


Figure 26: Simplified schematic of the single-phase system.

For the auto-transformer traction system it is necessary to add the auto-transformer impedance.

Some assumption can be made for the auto-transformer model, it can be considered a single-phase transformer with the windings connected in serial.

Assuming a higher efficiency level, the transversal branch can be neglected due to the small magnetization current. With this assumption the 180º degrees angle can also be neglected since the windings are in series. The model and the equivalent impedance are given by the equation (6.2). As can be seen by the following figure it is necessary to attribute more nodes for the modelization of this system. The auto-transformer impedance Z_1 and Z_2 can be considered as equal, therefore the equivalent impedance is the sum of Z_1 and Z_2.

The equivalent impedance of the auto-transformer can be measure with the short-circuit test.

[105] (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)
[106] (Ibdi.)

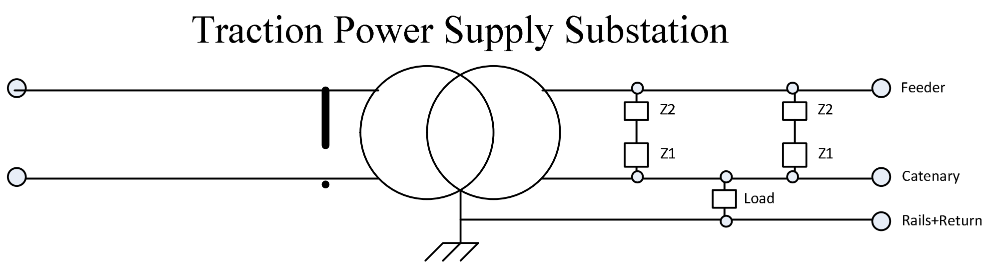


Figure 27: Simplified schematic of the auto-transformer system

In order to simulate this system it is possible to calculate each impedance per node and include in the admittances matrix. The equivalent impedance can also be measure with the short-circuit test.

6.2 Power Flow

The main goal of the power flow is the study of the electrical power system behavior in the network for different operating modes. With this evaluation is possible to predict the network performance through the evolution of the voltage levels over the network busbars. It is also possible to predict the quantity of energy generated in order to satisfy the consumer demands, quantify the system power losses, evaluate and identify safety measures in order to provide reliability and stability in the network.

The performed simulation only considers single-phase system although throughout this chapter the author proposes models and calculation methods for the auto-transformer system.

6.2.1 Calculation Method

To estimate the behavior of the traction power supply system this calculation method uses several procedures. The power consumption of traction vehicles was estimated through *Aubepine* method, as described in chapter 2.

Since *Aubepine* method requires the previous knowledge of the timetable and the vehicles behavior during the route it was necessary to use *Pulzufa* software. Through this software it was possible to simulate the vehicle consumption behavior for different types of traction vehicles in specific routes with programmed stops. The timetable and the calculation of the vehicles consumption through *Aubepine* method is included in annex 8.

The main goal of this chapter is to estimate the voltage drops, power losses, maximum length between power supply substations, power in the nodes and power flow between nodes.

The development of the power flow calculation method is based on the node method. The node method uses the *Kirchoff's* laws for currents. The concept of this method is to attribute nodes in the circuit branches. The *Kirchoff's* laws are applied to each of the circuit branch in relation to the balance node.

6.2.2 Power Flow Algorithm

The power flow algorithm used in this method relates voltages and currents. It is necessary to create one hypothetical scenario in this method in order to calculate the currents. This hypothetical scenario assumes one fix voltage value for one expected power.

The power flow algorithm is presented in annex 7.

The following matrix equations define the power flow algorithm:

The active and reactive power injected in each node (i), where P_G is the generation power and the P_C is the consumption power:[107]

$$P_i = P_{Gi} - P_{Ci} \tag{6.11}$$

$$Q_i = Q_{Gi} - Q_{Ci} \tag{6.12}$$

As described above will be considered in this method, voltages and currents which lead to linear equations:

$$[V] = [Z].[I] \tag{6.13}$$

The voltage drop in each node is calculated by the equation (6.13), the voltage in each node is the reference voltage minus the voltage drop.

Where the current is related with the injected power, with (n x 1) dimension:

$$[I] = \frac{[S]^*}{[V]^*} \tag{6.14}$$

The nodal impedance matrix is the inverse admittances matrix with (n x m) dimension.

The first matrix element includes the generating set impedance.

$$[Z] = [Y]^{-1} = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{6.15}$$

The calculus of the power in each node is given by the following equation matrix with (n x 1) dimension with the relation of the voltage and the current through the impedance: [108]

$$[S] = [V].[I]^* \tag{6.16}$$

[107] (Redes de Energia Electrica-Uma analise Sistémica, José Pedro Sucena Paiva)
[108] (Ibdi.)

The calculus of the power flow between nodes is given by the following equation:

$$\left[S_{m,n}\right]=\left[Y_{m,n}\right]^{*}.\left(\left|V_{m}\right|^{2}-V_{m}.V_{n}^{*}\right) \tag{6.17}$$

The power losses can be calculated by the sum of the power matrix since the power in the balance node is the sum of the power consumed by all nodes plus the losses in all sections. Is given by the following equation:

$$\text{Power Losses}=\text{sum}\left[S_{m,1}\right] \tag{6.18}$$

The calculus of the maximum length between traction power substations differs from the system used. For both systems the dimension of the last traction power substation was disregarded.

For the calculus of the single-phase system the author proposes the following considerations:

- Uniform load flow distribution;
- Constant headways between vehicles;
- Constant vehicles velocity;
- Both power traction substations have the same value of current and voltage.
- Disregard self and mutual inductions;

In order to calculate the maximum length between traction power substations in the single-phase system, it is necessary to analyze the maximum voltage drop in the pantograph.

With the maximum permissible voltage drop in the system divided by the maximum voltage drop in the pantograph the result can be assumed as a factor. Multiplying that factor by the length between nodes the result gives the maximum length between traction power substations.

For the auto-transformer system calculus the author proposes the following considerations:

- Uniform load flow distribution;
- Constant headways between vehicles;
- Constant vehicles velocity;
- Both power traction substations have the same value of current and voltage.
- Disregard self and mutual inductions;

In order to calculate the maximum length between traction power substations in the auto-transformer system, it is necessary to analyze the maximum voltage drop in the pantograph.

With the maximum permissible voltage drop in the system divided by the maximum voltage drop in the pantograph the result can be assumed as a factor. Multiplying that factor by the length between nodes the result gives the maximum length between traction power substations. Based on[109] results the author proposes as an initial approach the double length between traction power substations and the first auto-transformer compared with the length between auto-transformers. The author also proposes a better approach, estimated by trial and error.

[109] (Hyun-Su Jung, 2002)

7 Simulations

It was created a scenario in the electrical power traction grid operation in order to analyze the mathematical model performance for the single-phase system. This scenario relates three traction vehicles and three traction power supply substations.

7.1 Vehicles Characteristics

In this scenario, it was considered the ET 425 vehicle as regional train (RB), the BR 146 vehicle as regional express train (RE) and the BR 101 vehicle as Intercity train (IC).

It was considered an overall efficiency of 0,85 between the vehicle and the pantograph during the journey.

$$\text{For driving (Accelerating and Coasting)}: \text{Power}_{\text{Pantograph}} = \text{Power}_{\text{Mechanic}} \cdot \frac{1}{\eta} \tag{7.1}$$

$$\text{For braking (Regenerative)}: \text{Power}_{\text{Pantograph}} = \text{Power}_{\text{Mechanic}} \cdot \frac{1}{\eta} \tag{7.2}$$

The main characteristics of the traction vehicles consumption in the pantograph is presented in the table 13.

Traction Vehicles / Consumption (MW)	**ET 425**	**BR 146**	**BR 101**
Acceleration	2,23	3,86	5,44
Regeneration	-1,28	-2,32	-1,91
Constant speed	0,52	1,07	1,34
Stopped	0	0	0

Table 13: Active power consumption of the traction vehicles

7.2 Network Configuration

For this simulation was considered the traction network between the traction power supply substations of „Ulm – Amstetten“ and „Ulm – Aalen“.

Since the main concern of this mathematical model is to predict the network behavior in the power supply substations, this simulation simplifies the network configuration. It was created a scenario for the generation. The same generating set will feed all the power supply substations. The map of the DB (Deutsche Bahn) traction railway feeding system is included in the annex 4.

The selected route is between „Ulm – Stuttgart“. The consideration of single lines in this simulation it is due to the vehicles route direction.

The traction power system operation uses the parallel configuration. The schematic is included in the annex 5.

The contingency analysis was not simulated, although the traction power system considers the (n-1) criterion redundancy with the over dimension of two power transformers, both are feeding the traction power system at the same time. The impedance of the high voltage lines and the step-up transformer was not considered due to the upstream short-circuit power. As mentioned above the main concern of this model is to predict the network behavior in the power supply substations for operating states variations. This network considers the node number 1 as the balance busbar. The nodes number 2, 3, 4, 5, 6, 7 shows the PQ busbars.

The following figure shows the schematic of the network configuration:

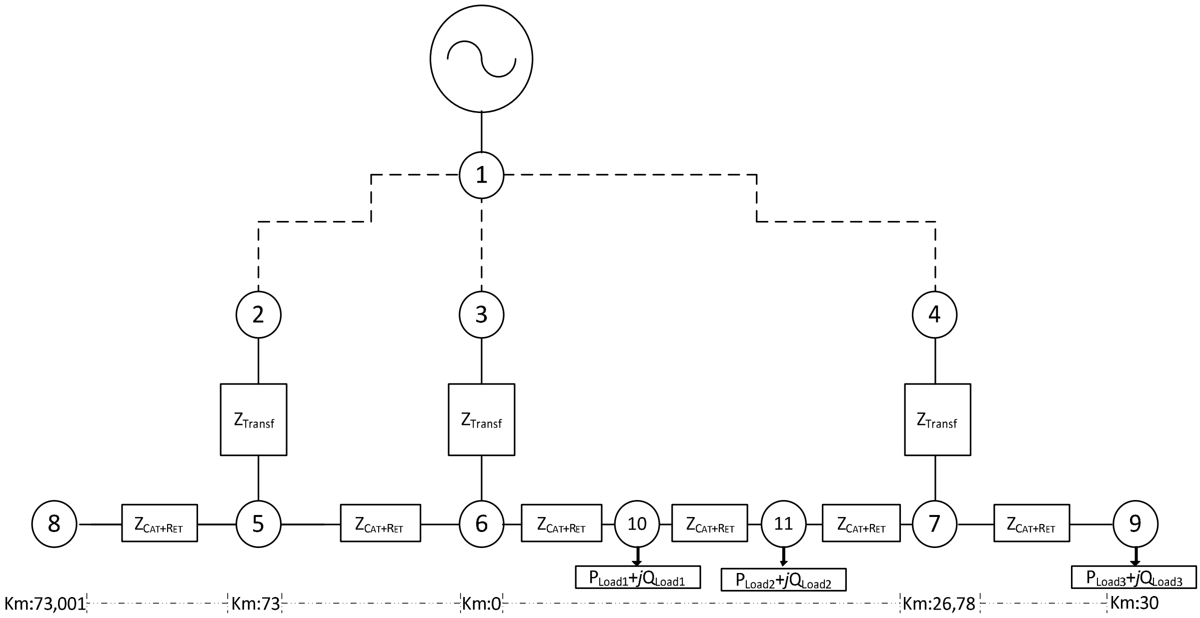


Figure 28: Network configuration

7.2.1 Power Supply System

In the upstream is considered at the entrance of the power supply substations, the short-circuit power. These values were assumed by the author in order to calculate the upstream equivalent impedance.

$$S_{cc1} = 1500 \text{ MVA} \quad \rightarrow Z_{cc1} = j.\frac{V_b^{\,2}}{S_{cc1}} = \frac{(15\times10^3)^2}{1500\times10^6} = j0,015\Omega \tag{7.3}$$

$$S_{cc1} = 2500 \text{ MVA} \quad \rightarrow Z_{cc1} = j.\frac{V_b^{\,2}}{S_{cc1}} = \frac{(15\times10^3)^2}{2500\times10^6} = j0,09\Omega \tag{7.4}$$

$$S_{cc1} = 2000 \text{ MVA} \quad \rightarrow Z_{cc1} = j.\frac{V_b^{\,2}}{S_{cc1}} = \frac{(15\times10^3)^2}{2000\times10^6} = j0,1125\Omega \tag{7.5}$$

The power dimension of the traction power substations is the sum of the maximum apparent power consumption of the vehicles in (MVA).

Through the table 14 the maximum power is 14 MVA. The overload of the traction vehicles is regarded by the auto-transformer overload. Due to the lack of data on the traction vehicles, the cos φ was attributed by the author.

Traction Vehicles / Consumption	ET 425	BR 146	BR 101
Apparent power (MVA)	2,49	4,35	6,9
Active power (MW)	2,35	4,2	6,4
Reactive power (Mvar)	0,8	1,14	2,58

Table 14: Power consumption of the traction vehicles[110]

Due to a lack of data the author attributes to the generator set: X_d : 12%, cosφ:0.9, U_n:15 kV and also P_n:20 MW. Due to the expected value of nominal power from the vehicles, the author considers a possible increase on the circuits to be feed by the same generator set and assigns the nominal power of 20 MW to this generator set. The impedance is given by:

$$S_n = \frac{P_n}{\cos\varphi} = \frac{20\times10^6}{0.9} = 22\text{MVA} \quad (7.6)$$

$$Z_G = X'_d(\Omega) = \frac{x'_d(\%)}{100}.\frac{V_n^2}{S_n} = j\frac{12}{100}.\frac{(15\times10^3)^2}{22\times10^6} = j0.54\Omega \quad (7.7)$$

The power dimension of the traction power substations is the sum of the maximum apparent power consumption of the vehicles in (MVA). The u_{cc}=8% was attributed by the author due to the a lack of data on the traction vehicles. The author also considered the high efficiency of the transformer; the losses in the core are negligible due to the high efficiency.

$$Z_T = \frac{u_{cc}(\%)}{100}.\frac{V_b^2}{S_n} = j\frac{8}{100}.\frac{(15\times10^3)^2}{14\times10^6} = j1.7\times10^{-4}\Omega \quad (7.8)$$

Since the power traction substation uses two power transformers that feed at the same time and in parallel, the calculate impedance in the equation (7.8) is divided by two.

The contact, catenary, return wire and rails impedance is calculated per km. In this simulation it was only considered the single-phase system with the f=16,7 Hz.

The materials used in this simulation are: [111]

- Contact wire: CuMg AC-120;
- Catenary wire: BZII 120 mm^2;
- Rails: UIC 60;
- Return conductor: 243-AL1;

The equivalent impedance is: $Z_{eq} = 0.068 + j0.071(\Omega / \text{km})$

110 (DB-Baureihe 425 (1999), 2012), (Bombardier TRAXX, 2011), (DB-Baureihe 101, 2009)
111 (Kiessling, 2009)

7.2.2 Simulation Results

This simulation has regarded the *Aubepine* results. Through *Aubepine* results it was taken into consideration the average consumption per train during the track, in order to calculate the current for the worst case scenario 12 kV.

The author had considered that the ET 425 traction vehicle did not influenced the consumption supplied through the traction power supply substation after the minute two, since it was outside of the traction power supply substation.

The values of the vehicles energy consumption and the headways of the following table are also included in the power flow algorithm:

Min	**Distance Between Nodes (km)**						**Vehicles Consumption (MW)**		
	6-10	**10-11**	**7-11**	**7-9**	**5-8**	**6-5**	**ET 425 Node 9**	**BR 101 Node 10**	**BR 146 Node 11**
0,00	0,00	0,02	26,78	0,92	0,00	73,00	2,49	4,59	4,07
1,00	0,02	0,50	26,28	1,92	0,00	73,00	2,49	4,59	4,07
2,00	0,50	0,50	25,78	3,22	0,00	73,00	2,49	4,59	4,07
3,00	2,00	1,00	23,78	3,22	0,00	73,00	0,00	4,59	4,07
4,00	4,00	1,00	21,78	3,22	0,00	73,00	0,00	4,59	4,07
5,00	6,00	1,00	19,78	3,22	0,00	73,00	0,00	4,59	4,07
6,00	8,00	1,00	17,78	3,22	0,00	73,00	0,00	4,59	4,07
7,00	10,00	1,00	15,78	3,22	0,00	73,00	0,00	4,59	4,07
8,00	12,00	1,00	13,78	3,22	0,00	73,00	0,00	4,59	4,07
9,00	14,00	1,00	11,78	3,22	0,00	73,00	0,00	4,59	4,07
10,00	16,00	1,00	9,78	3,22	0,00	73,00	0,00	4,59	4,07
11,00	18,00	1,00	7,78	3,22	0,00	73,00	0,00	4,59	4,07
12,00	20,00	1,00	5,78	3,22	0,00	73,00	0,00	4,59	4,07
13,00	21,00	2,00	3,78	3,22	0,00	73,00	0,00	4,59	4,07
14,00	23,00	2,00	1,78	3,22	0,00	73,00	0,00	4,59	4,07
15,00	24,00	2,00	0,78	3,22	0,00	73,00	0,00	4,59	4,07
16,00	26,00	0,78	0,00	3,22	0,00	73,00	0,00	4,59	4,07

Table 15: Power Flow introduction data

The following figure shows the voltage and the voltage drop existing in the generation node over the load variations. During the load variations the generating set behavior shows a higher stability.

The current distribution to the traction power supply substation nodes confirms the parallel operational system.

In the beginning of the route the current distribution to the second node is higher due to the vehicles consumption in the node three. According with the vehicles motions, the current in node three decreases for the same motive. The opposite occurred in the node four since the vehicles motion is in the direction of the traction power supply substation represented by node four.

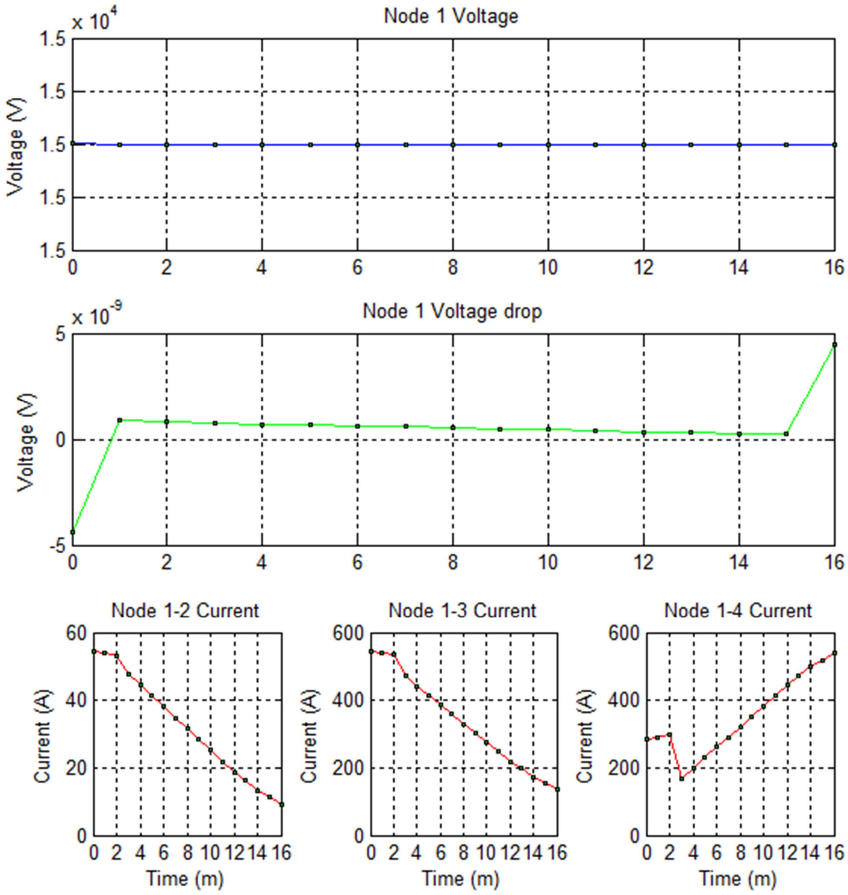


Figure 29: Evaluation of the behavior in the node nº1

The figure 30 is related to the second node, the behavior is the same compared with the node nº 5, since the point of connection does not have any other connection branch. Due to the traction vehicles motion in the opposite side from the traction supply substation, the voltage tended to level off as well as the currents.

The annex 6 contains the current and voltage behavior related with the others nodes nº 3, nº 4, nº 6, nº 7 and nº11.

The same behavior occurs in the node 3 and 6 with the vehicles approach to the traction power supply substations. The opposite behaviour occurs in the node 4 and 7.

The voltage tends to stabilize to the nominal voltage in the opposite substation related with the vehicles motion and tends to decrease with the approach of the vehicles related to the traction power substation.

The node 11 have the same behaviour as the node 10 as can be seen in the figure 31.

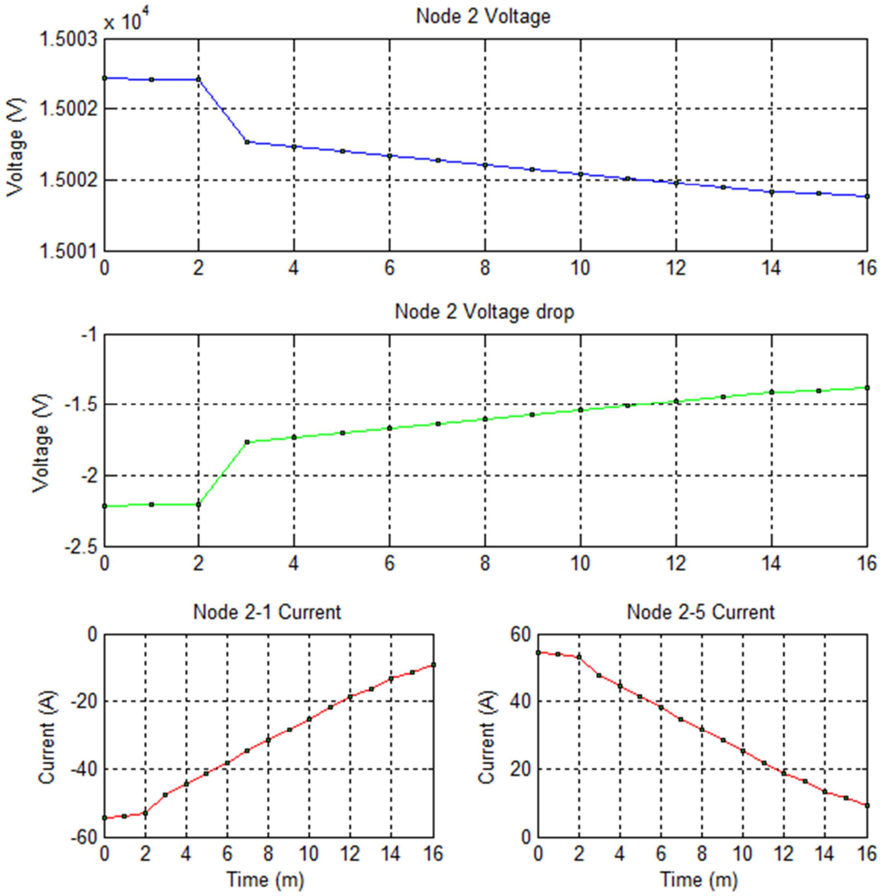


Figure 30: Evaluation of the behavior in the node nº2

The figure 31 shows the BR 101 vehicle behavior during the route. In this figure it is shown the maximum value of voltage drop. The maximum voltage drop occurs in the minute nº 9, due to the incomplete travel between traction power substations. The author assumes the end of this simulation when the BR 146 vehicle finishes the complete travel in order to see the behavior of the voltage drop in the pantograph.

As can be seen in the annex 6 with the vehicle BR 146 behavior the maximum voltage drop occurs in the minute nº 8, in the middle of the feeding section area between traction power supply substations.

The author expects the same behavior when the BR 101 vehicle completes its journey.

Since this vehicle has the higher level of consumption, the maximum voltage drop compared with the other vehicles will occur with the BR 101 vehicle.

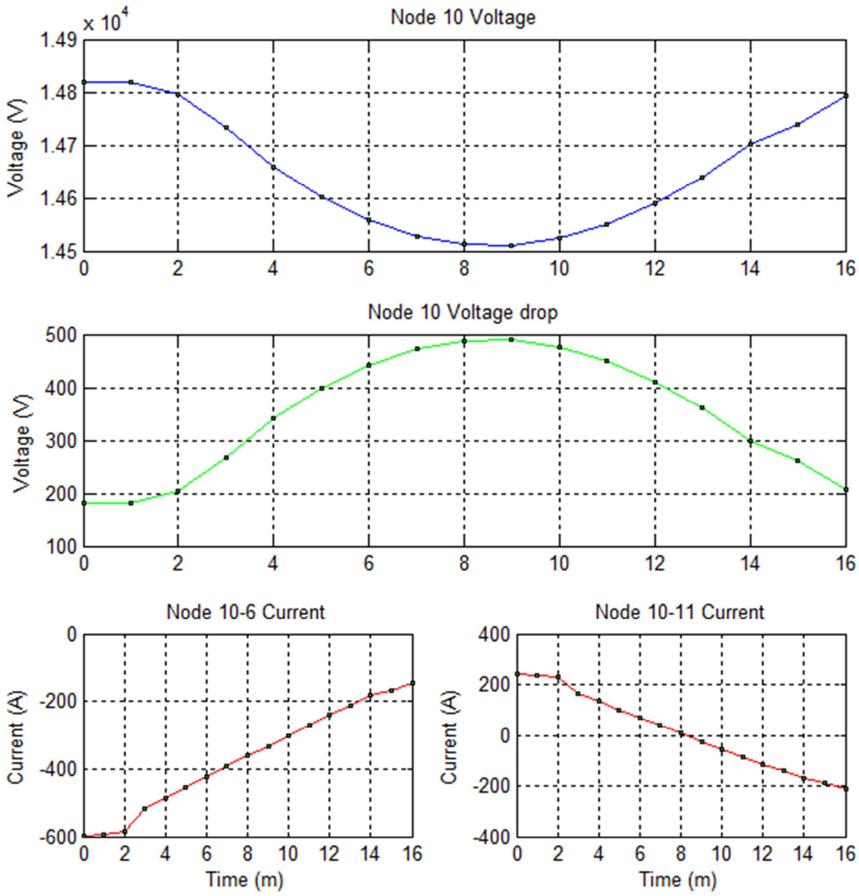


Figure 31: Evaluation of the behavior in the node nº10

The figure 32 shows the apparent power behavior of the traction power supply substations. As can be seen the power behavior in the node nº 6 and nº 7, had the opposite behavior.

The behavior is uniform except when the loads are near the traction power supply substations.

The difference between values of node nº 6 and nº 7 is related to the compensation of the adjacent of the traction power supply substations, since the power in node nº 6 is compensated by node nº 5. This is one of reasons for the power variation in that particular node, the other main reason is due to the inexistence of load distribution between the section of node nº 5 and node nº 6.

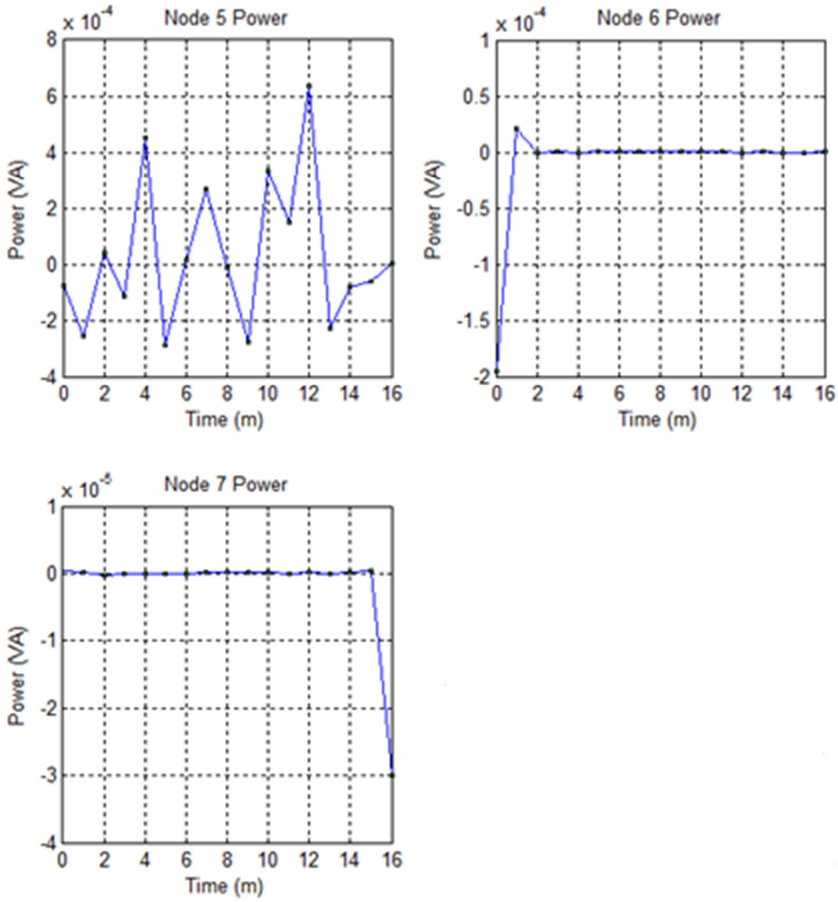


Figure 32: Evaluation of the apparent power behavior in the traction power supply substations

The figure 33 represents the power losses in the traction power supply substations. As the loads moved from the traction power supply substation, the impedance is higher. Also in this case the power consumption of the vehicles was considered as constant, which leads to higher currents in the minute 8 due to the voltages drops. This is the main reason for the higher power losses in the electrical network.

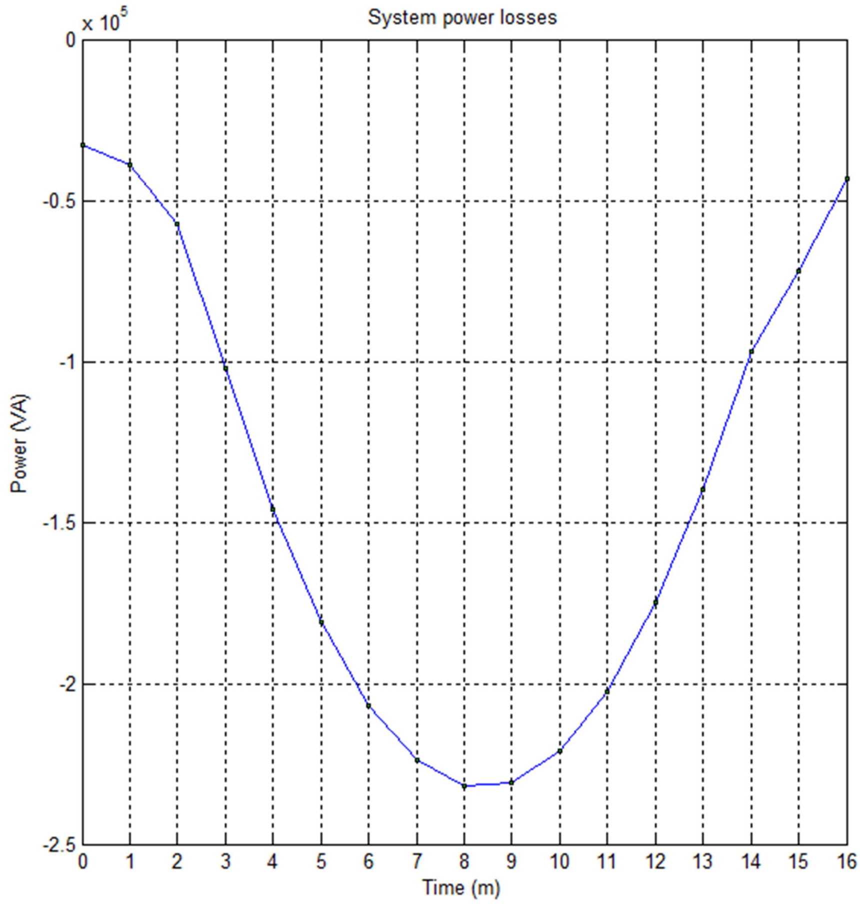


Figure 33: Evaluation of the power losses in the system network

The power flow between nodes 5-2, 6-3 and 7-4 are given by the figure 34.

The behavior of the power flow in node 5-2 it is similar to the node 6-3 due to the opposite vehicles journey related with those traction power substations.

The occurred power flow in nodes 6-3 and 5-2, has the opposite behavior compared with the power flow between nodes 7-4, as expected.

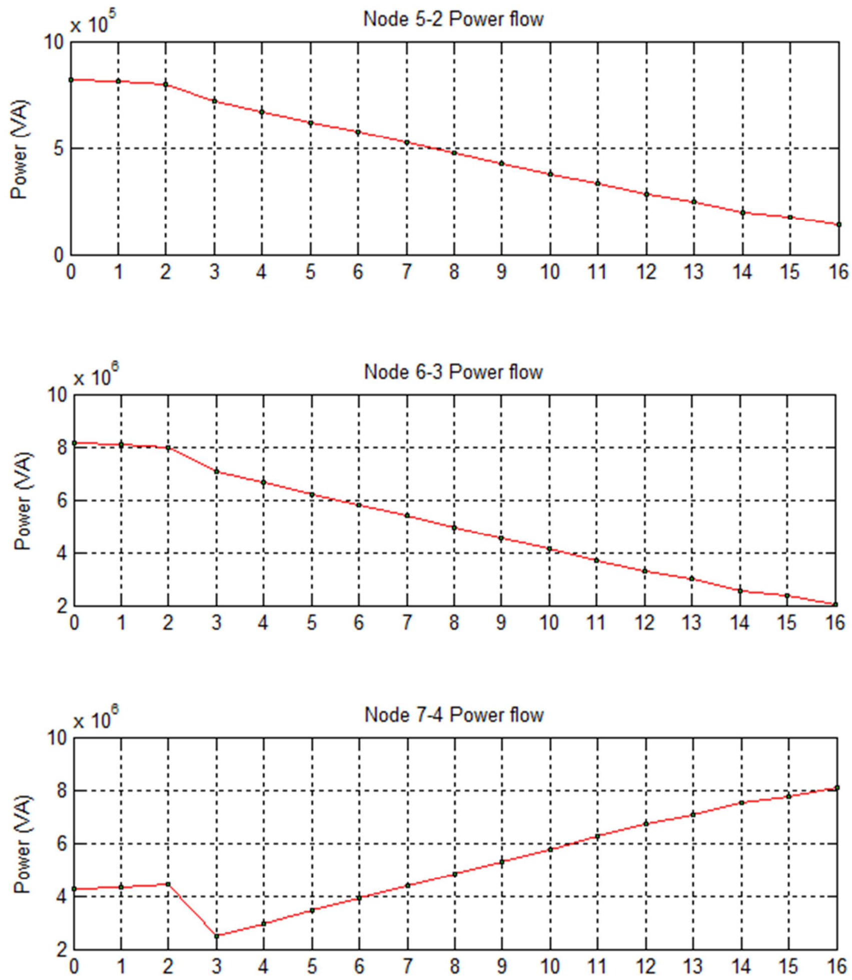


Figure 34: Evaluation of the power flow in the 5-2, 6-3,7-4 nodes.

For the simulation of the maximum length only one traction vehicle was considered. This simulation is presented in the following figure.

The approach made in this simulation reflects the possible maximum length, also the error rate can be considered due to the EN 50163 and IEC 60850. The load variations were not considered in this model, although it can be considered as an initial estimation of the maximum admissible lenght.

The following table indicates the introduction data in order to obtain the admissible maximum value between traction power substations.

Min	Distance Between Nodes (km)						Vehicles Consumption (MW)		
	6-10	10-11	7-11	7-9	5-8	6-5	ET 425 Node 9	BR 101 Node 10	BR 146 Node 11
0,00	0,00	0,00	396,34	0,92	0,00	73,00	0,00	0,00	4,07
1,00	24,77	0,00	371,57	1,92	0,00	73,00	0,00	0,00	4,07
2,00	49,54	0,00	346,80	3,22	0,00	73,00	0,00	0,00	4,07
3,00	74,31	0,00	322,03	3,22	0,00	73,00	0,00	0,00	4,07
4,00	99,09	0,00	297,26	3,22	0,00	73,00	0,00	0,00	4,07
5,00	123,86	0,00	272,49	3,22	0,00	73,00	0,00	0,00	4,07
6,00	148,63	0,00	247,71	3,22	0,00	73,00	0,00	0,00	4,07
7,00	173,40	0,00	222,94	3,22	0,00	73,00	0,00	0,00	4,07
8,00	198,17	0,00	198,17	3,22	0,00	73,00	0,00	0,00	4,07
9,00	222,94	0,00	173,40	3,22	0,00	73,00	0,00	0,00	4,07
10,00	247,71	0,00	148,63	3,22	0,00	73,00	0,00	0,00	4,07
11,00	272,49	0,00	123,86	3,22	0,00	73,00	0,00	0,00	4,07
12,00	297,26	0,00	99,09	3,22	0,00	73,00	0,00	0,00	4,07
13,00	322,03	0,00	74,31	3,22	0,00	73,00	0,00	0,00	4,07
14,00	346,80	0,00	49,54	3,22	0,00	73,00	0,00	0,00	4,07
15,00	371,57	0,00	24,77	3,22	0,00	73,00	0,00	0,00	4,07
16,00	396,34	0,00	0,00	3,22	0,00	73,00	0,00	0,00	4,07

Table 16: Maximum length introduction data

The maximum length between traction power supply substations is 396,34 km. Through this value the maximum voltage obtained in the minute 8 as the value of 12,170 V as can be seen in the following figure.

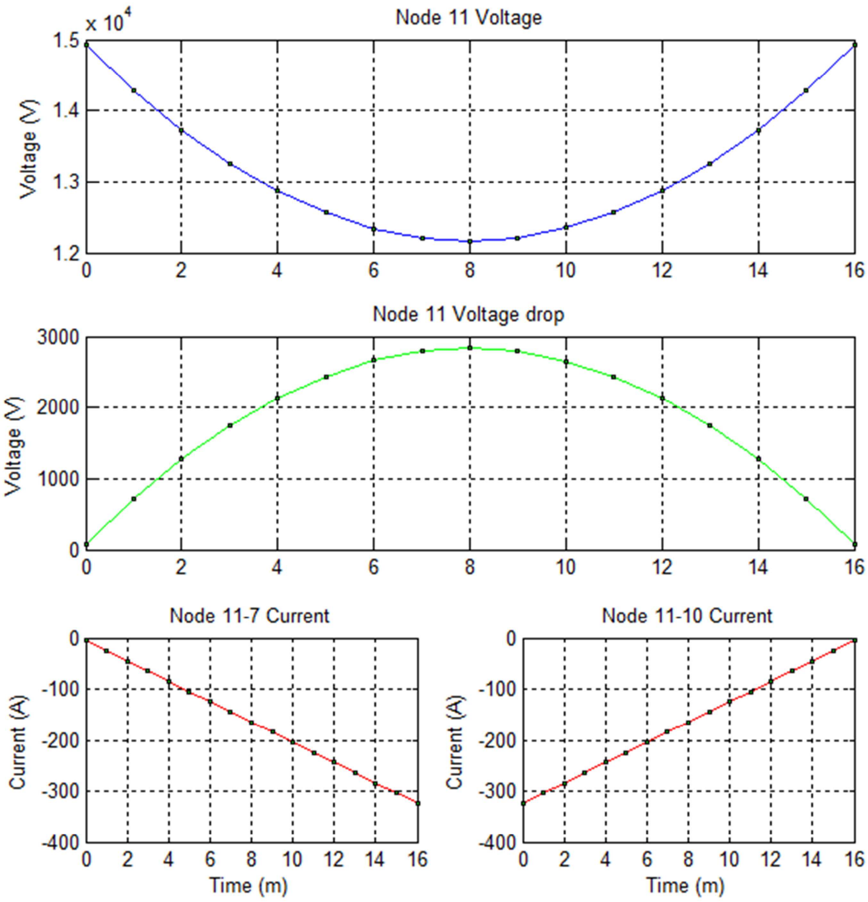


Figure 35: Evaluation of the admissible voltage drop due the maximum length between traction power substations

8 Conclusions and Future Work

The aim of this work is to characterize and simulate the interaction between the traction power supply system and the traction vehicles planning.

Calculation methods and models for driving dynamics, energy and traction power supply systems were study and developed in order to simulate the interaction between the subsystems of the railway traction system. Therefore the calculation methods and the implemented models in this work uses several approaches as well as some assumptions in order to simplify the complexity of railway traction system.

The traction vehicles behavior in the traction supply system trought the *Pulzufa* software and *Aubepine* method were used as the input data in the power flow calculation. The results of the power flow calculation can only be considered as a first approximation and should be compared with a traction power supply and the driving dynamics simulation software.

The obtained results for the single-phase system provides satisfactory results to preliminary calculations that do not require great precision or detailed knowledge in relation to the railway traction system.

The algorithm for the maximum permissible length between substations did not reveal the desirable robustness. Through this algorithm some limitations were observed due to the approximation value obtained and operating modes. It is important to overtake these limitations in all the admissible operating modes as well as to attain an accurate value.

Computationally the implemented power flow algorithm is a viable alternative due to the fast convergence and minimal parameter configuration although it is less friendly compared with the analysed softwares in the previous chapters.

The power flow calculation method was only simulated for the single-phase system in the worst case scenario, it should be also implemented and analyzed for the auto-transformer system as well for different load variations.

The model of the traction vehicle should be integrated in this calculation method with the new technologies mentioned in this work.

In the auto-transformer system the author considers that a calculation algorithm should be improved in order to estimate the maximum length between the power traction substation and the first auto-transformer as well as between auto-transformers. In this algorithm it was not considered the dimension of the last traction power substations in both systems.

The criterion redundancy (n-1) was considered but it was not simulated. The contingency analysis should be tested in order to predict the system behavior and to insure the correct dimensioning.

The knowledge gain with this work provides the basis knowledge of the traction system, further developments in the following points related above should be considered in a future work.

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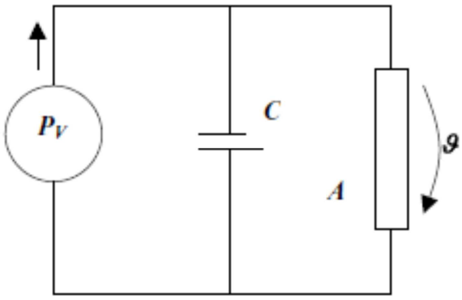
Annex 1 - Motor Thermal Model



$$P_V = C.\frac{d\vartheta}{dx}.A.\vartheta$$

P_V:	Power losses
C:	Heat capacity of the machine
ϑ :	Heat transfer capability of the machine
A:	Overheating in the winding

$$\vartheta = \theta_e.\left(1 - e^{-\frac{t'}{\tau}}\right) + \theta_a.e^{-\frac{t}{\tau}}$$

θ_e :	End of the overheating
θ_a :	Initial value of the overheating
τ :	Constant heating
t' :	Reference time
t	Load time

DC Traction Motor:

$$W_{el,g} = U.I.t$$

Single-phase AC traction motor:

$$W_{el,w} = U.I.\cos\delta\, t$$

Three-phase AC traction motor:

$$W_{el,d} = \sqrt{3}.U.I.\cos\delta t$$

The electrical power is given by:

$$P_{el} = U.I = R.I^2$$

The electrical work can be written in function of the current, electrical work is:

$$W_{el} = f\left(I^2\right) = I^2.\,R.t \Leftrightarrow I = \sqrt{\frac{W_{el}}{R.t}}$$

The load time can be written in function of the:

$$t = \frac{W_{el}}{P_{el}}$$

The overtime temperature of the traction motor is proportional to the square of this one, at the load time t used. Is given by the equation:

$$\frac{t}{t'} = \frac{I_m^2}{I_d^2} \Leftrightarrow t = \frac{I_m^2}{I_d^2}.t'$$

t' : Reference time in (s)
t Load time in (s)
I_m : Average current in (A)
I_d Nominal current in (A)

$$\vartheta_{zul} = \vartheta_{max} - \vartheta_V - \Delta\vartheta$$

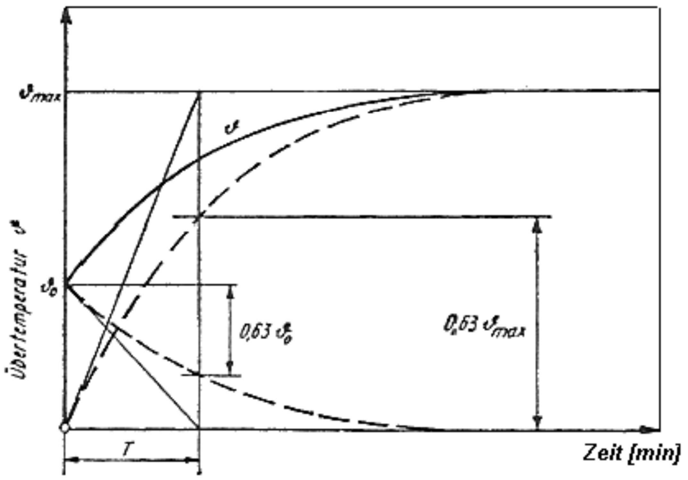
ϑ_{zul} : Temperature limit in K
ϑ_{max} : Admissible temperature in °C
ϑ_V : Ambient air temperature in °C
$\Delta\vartheta$: Difference of temperature in K

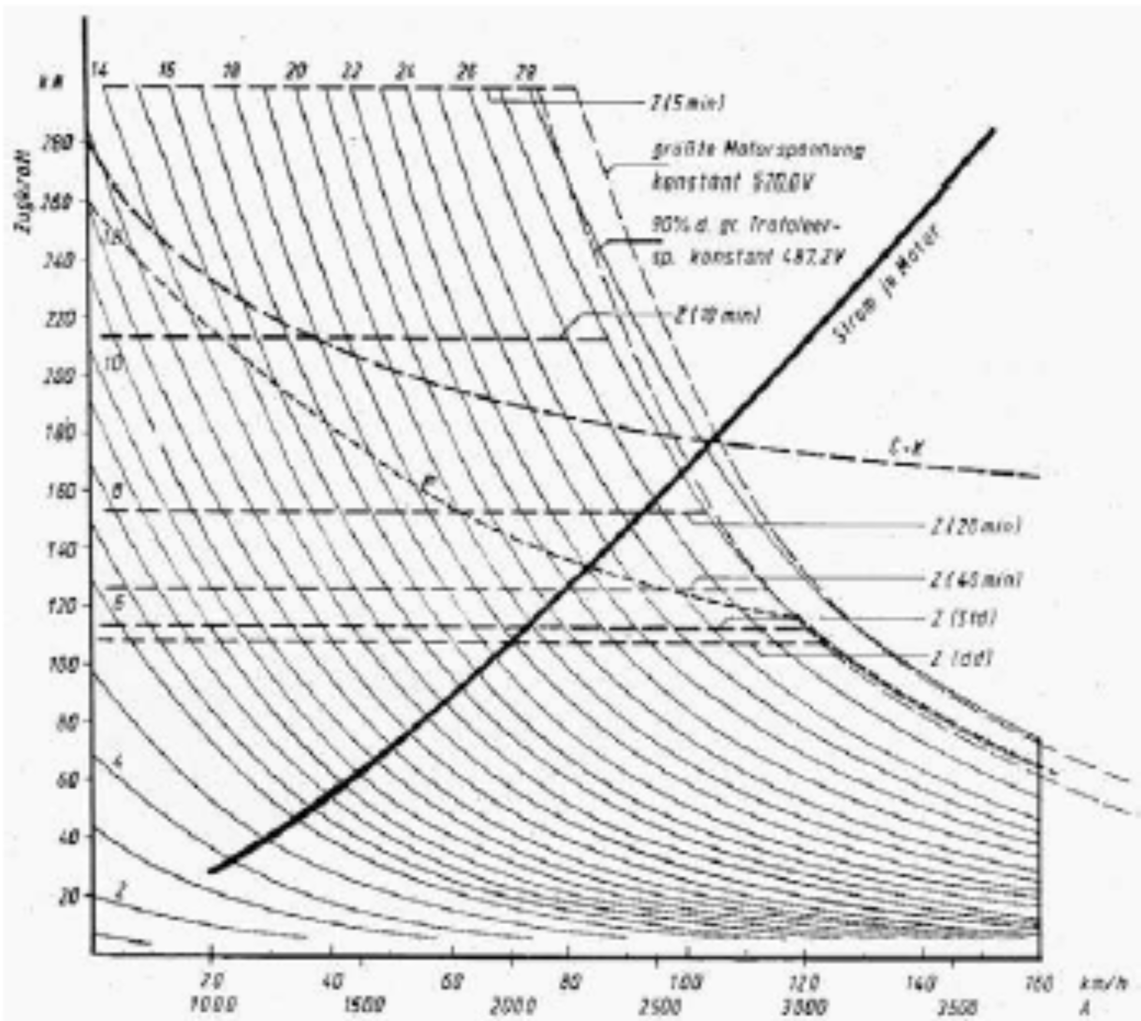
$$C_{QM} = m_M.\bar{c}$$

C_{QM} : Heat capacity in Ws/K
m_M : Traction engine mass in kg
$\bar{c}$: Average heat capacity in the traction motor Ws/kg.K .

$$\Delta Q = \int_{\vartheta_0}^{\vartheta_{max}} \lambda.A.d\vartheta \Leftrightarrow \Delta Q = \lambda.A.(\vartheta_{max} - \vartheta_0)$$

Q: Heat flow in input or lost heat flow , J/s = W
λ:. Heat transfer coefficient, W/K.m^2
A: Heat transfer surface area, m^2
ϑ_{max} : Admissible permanent overheating in °C
ϑ_0 : Inicial overheating in °C





Monophasic Motor Overheating Diagram[112]

[112] (Lehmann, 2006)

Annex 2 - Power Supplies Characteristics

Country	Characteristics		
	Type of Power Supply	Stagger (mm)	Pantograph width (mm)
France High-speed lines Conventional lines	 AC 25 kV 50 Hz DC 1,5 kV	 200 200	 1450 or 1600 1600 or 1950
Germany High-speed lines Conventional lines	 AC 15 kV 16,7 Hz AC 15 kV 16,7 Hz	 300 400	 1600 or 1950 1950
Austria Conventional lines	 AC 15 kV 16,7 Hz	 400	 1950
Denmark Conventional lines	 AC 25 kV 50 Hz	 275	 1950
Spain High-speed lines Conventional lines	 AC 25 kV 50 Hz DC 3 kV	 300 or 200 200	 1600 and 1950 1950
Netherlands High-speed lines Conventional lines	 AC 25 kV 50 Hz DC 1,5 kV	 200 350	 1600 1600 or 1950
Portugal Conventional lines	 AC 25 kV 50 Hz	 200	 1450 or 1600
Italy High-speed lines Conventional lines	 DC 3 kV or AC 25 kV 50 Hz DC 3 kV	 300 300	 1600 1600
Belgium High-speed lines Conventional lines	 AC 25 kV 50 Hz DC 3 kV	 200 350	 1450 or 1600 1950
Great Britain High-speed lines Conventional lines	 AC 25 kV 50 Hz DC 0,75 kV or AC 25 kV 50 Hz	 200 230	 1600 1600

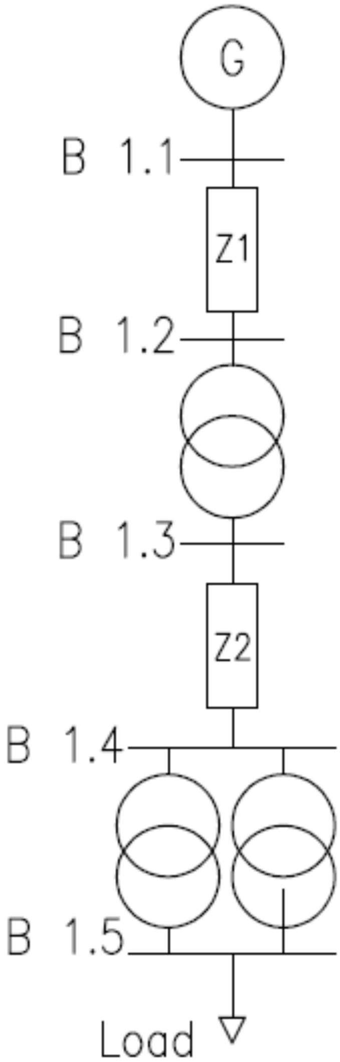
Main characteristics of traction power supplies systems in Europe[133]

113 (Kiessling, 2009)

Annex 3 - Influence of Variations in Traction Systems

Traction Power Generation (Power Plant) – Traction Power Distribution (Substation)		
Bus Bar	**Type of Variations in the Electric Power System**	**Consequences**
B 1.1	**1.** Amplitude of the nominal voltage; **2.** Non constant frequency, the synchronous value;	**1.** The voltage amplitude is controlled by the excitation field of the generators, it is necessary to control the voltage amplitude in order to maintain the admissible limit values. If the admissible limit voltage value is not regarded it is not possible to ensure the desired power level in the load as well as the efficiency levels; **2.** If the admissible limit value of frequency is not regarded it is not possible to ensure the synchronism in the generators in order to maintain the dynamic balance between the power generated and power required by the required loads. Reducing the frequency in relation to a synchronous power generating causes insufficient for the requested load and may lead to the generator disconnecting. When the frequency exceeds a synchronous generation, means an excess of generated energy. This is caused by variations in the speed of the turbines and generators due to temporary imbalances between generation and demand;
B 1.2	**1.** Short-circuit;	**1.** As a result of an interruption in one conductor in a three-phase system, overvoltage may occur. After the transient phenomenon inherent to a short-circuit between phase and neutral, the current is limited only by the power system impedance and the impedance of the conductors. Short circuits produce higher values of current intensity. The three phase short-circuit is more harmful due to the high current value. If the protections do not act in proper time it can create in the network the avalanche breakdown. As close the short-circuit is from the generation higher the system disturbance.
B 1.3	**1.** Unbalanced phases; **2.** Short-circuit;	**1.** The unbalanced phases are caused by the asymmetric distribution of loads through the phases. The asymmetric distribution gives rise to unbalanced currents, which, in turn, cause vibrations as well as unbalance voltage (overvoltage, overcurrent) in the three phases, thereby decreasing their performance. The transformer is sensitive to unbalanced phases. It could cause overheating and therefore the isolation destruction may result in withdrawn from service for repair or replacement. **2.** For the transformer a short-circuit may lead to his substitution due to high currents in it which are awfully rising winding temperature. There is distortion of the windings, weakening of the insulation system by friction and mechanical stress.

	3. Undervoltage; **4.** Overvoltage; **5.** Medium frequency disturbances;	**3.** Under voltage (voltage dip), a sudden reduction of the voltage at a point in an electrical system followed by voltage recovery after a short period of time from a few cycles to a few seconds can cause operation failed, shutdown or additional losses due defects in the network, maneuvers in the network, malfunction of the voltage regulators magnetization of the transformer. **4.** Overvoltage is an increase of the value of the voltage. This can cause the dielectric breakdown between parts of the coil in stray dots of the winding and resulting higher losses since it will be working in overload decreasing the lifetime of it. **5.** Since the transformer is a device with ferromagnetic core saturated this can cause medium frequencies disturbances and will contribute to the appearance of harmonics and inter harmonics in the network create a series of problems such as resonances between parallel transformers, loads and compensators. These variations will cause a non-normal transformer operation existing the possibility of burning it, as well as unwanted phenomena such as voltage and increase harmonic distortion on the network.
B 1.4	**1.** Short-circuit	This phenomena was explain and similar with the bus bar 1.2.
B 1.5	**1.** Unbalanced phases; **2.** Short-circuit; **3.** Under-voltage; **4.** Medium frequency disturbances;	The points **1, 2, 3** and **4** was explain in the bus bar 1.2, although if the distribution network with distributed generation, the contributing for the short-circuit current from the substation will decrease. This decrease is responsible for the decreased sensitivity of the protection system. The decrease of sensitivity consists in increasing the open time of the protection. Short circuits with high resistance and short-circuits between phases can reduce the network contribution which may lead the protection doesn't detect the defect without acting on time. **NOTE:** For railway the substation transformer uses special connections (Scott or Stelnmetz) in order to ensure the biphasic system connection (90 ° offset voltages). This system allows the connection of loads monophasic or biphasic. If the load distribution biphasic or monophasic loads are balanced, this connection behaves in the presence of the network like a balance three phase load.



High Voltage Network-Traction Power Substation

Type of System	Type of Variations	Consequences
Single - Phase AC System	**1.** Short-circuit contact line	**1.** As a result of an interruption in the contact line if the protections do not act in the proper time the current will increase and the voltage will decrease (voltage dip) as well the frequency. There is the possibility of the generator disconnection Uc<1% (interruption of supply voltage).
	2. Short-circuit return line	**2.** Risk of overvoltage leading to additional losses. Safety systems will also be affected (signaling)
	3. Starting of a high load	**3.** With the start of high loads it also can occur voltage dip as flickers (voltage fluctuation) which will occur power oscillations, implies losses in the network
	4. Load variation	**4.** It can contribute for over voltage if the loads are removed or under voltage if loads are inserted in the network
	5. Non linear loads	**5.** Will contribute to the appearance of harmonics and inter harmonics in the network and will add additional losses.
	6. Lightning strikes	**6.** It will add over voltages, this was explained in B 1.3_4. On the edge it can disconnect the generation.

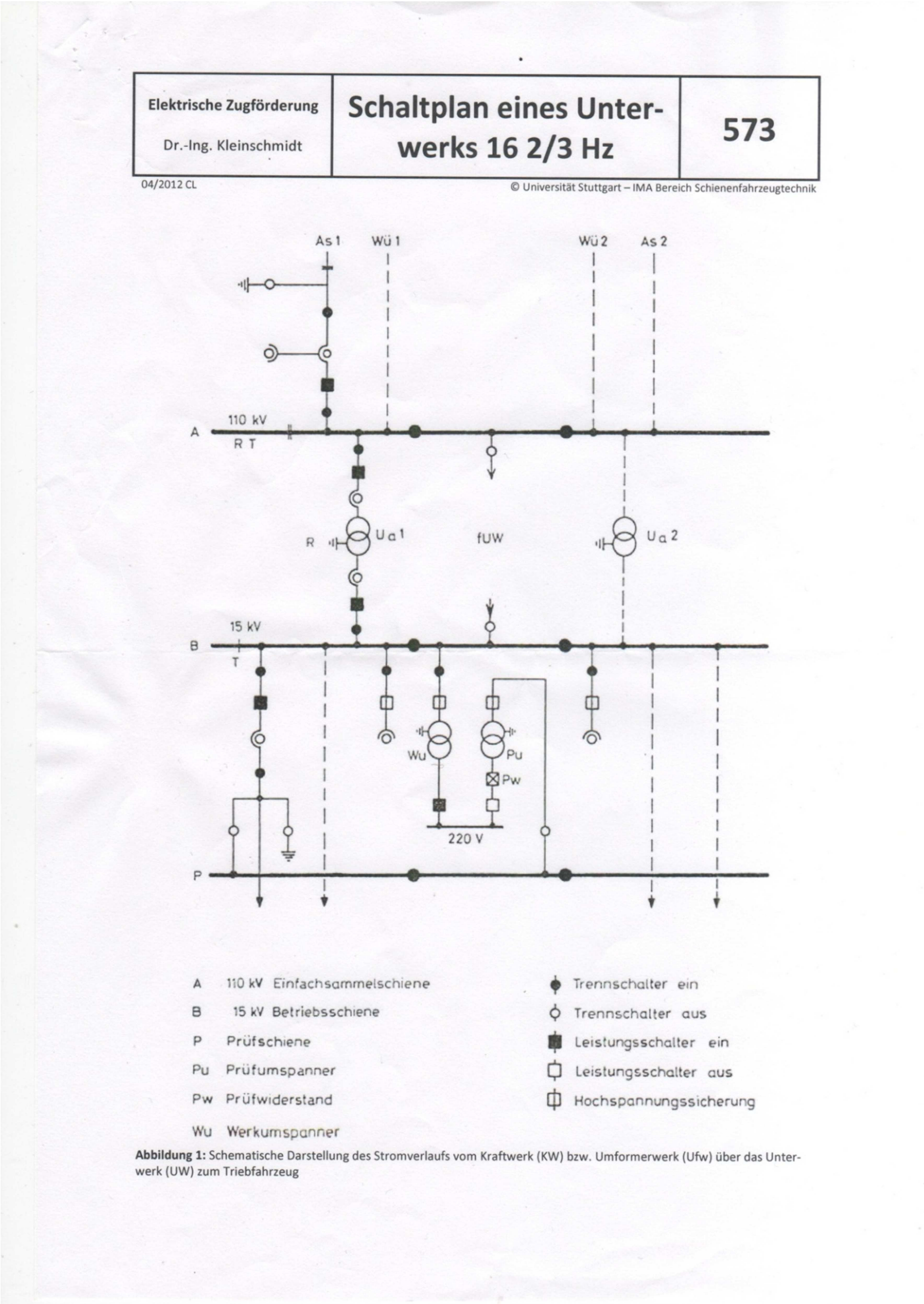
Type of System	Type of Variations	Consequences
Auto Transformer-System (AT)	**1.**Short-circuit contact Line **2.**Short-circuit return line (rail) **3.** Starting of a high load **4.** Load variation **5.** Non linear loads **6.** Lightning strike **7.** Auto-transformer **8.** Short-circuit in the return conductor	The point 1,2,3,4,5 and 6 was explain in the bus bar 1.2 in this system this types of variations have the same influence. 7. In this point it has the same characteristic that the bus bars 1.3 although if a short-circuit occurs in this transformer, the impedance is higher and also the losses are higher, since the impedance seen by the substation increase. If the impedance increases the current also will increase, voltage drop can occur. This also will affect the capability of traffic by reducing it, also the electromagnetic fields will increase. 8. This point it is similar to the point 2 since the current drain by those two conductors, although since the neutral conductor of the transformer in the limit it can put the auto-transformer out-of-commission. All the return current will be made by the rail in that section. Since the return current is in phase opposition this can create unbalances voltages.

Annex 4 - Traction Power Supply Substations

16,7-Hz-Energieerzeugungs-, übertragungs- und verteilungsanlagen in Deutschland am 1. Januar 2011

Quelle: Zeitschrift "Elektrische Bahnen" 2011 Heft 1-2

Annex 5 - Parallel Configuration of the Traction Power Supply Substation



Elektrische Zugförderung Dr.-Ing. Kleinschmidt	Schaltplan eines Unter- werks 16 2/3 Hz	573

04/2012 CL

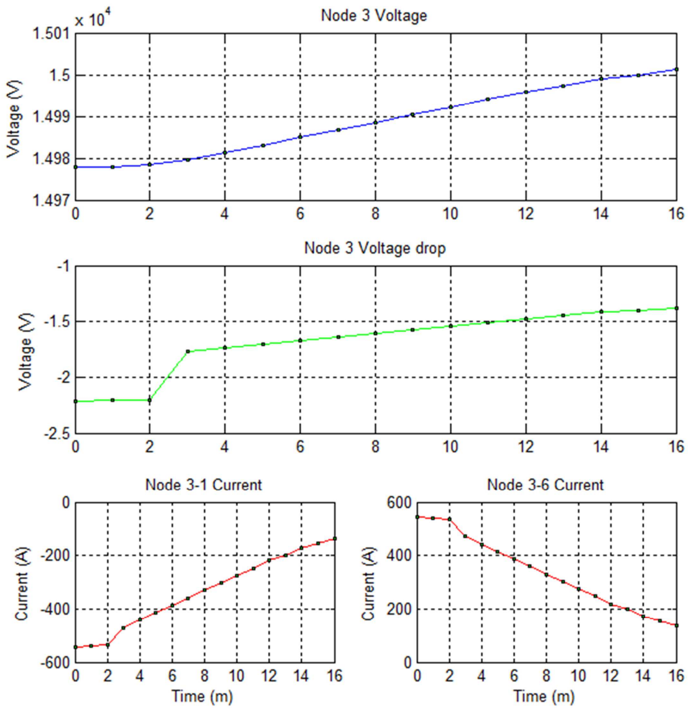
A 110 kV Einfachsammelschiene
B 15 kV Betriebsschiene
P Prüfschiene
Pu Prüfumspanner
Pw Prüfwiderstand
Wu Werkumspanner

Trennschalter ein
Trennschalter aus
Leistungsschalter ein
Leistungsschalter aus
Hochspannungssicherung

Abbildung 1: Schematische Darstellung des Stromverlaufs vom Kraftwerk (KW) bzw. Umformerwerk (Ufw) über das Unterwerk (UW) zum Triebfahrzeug

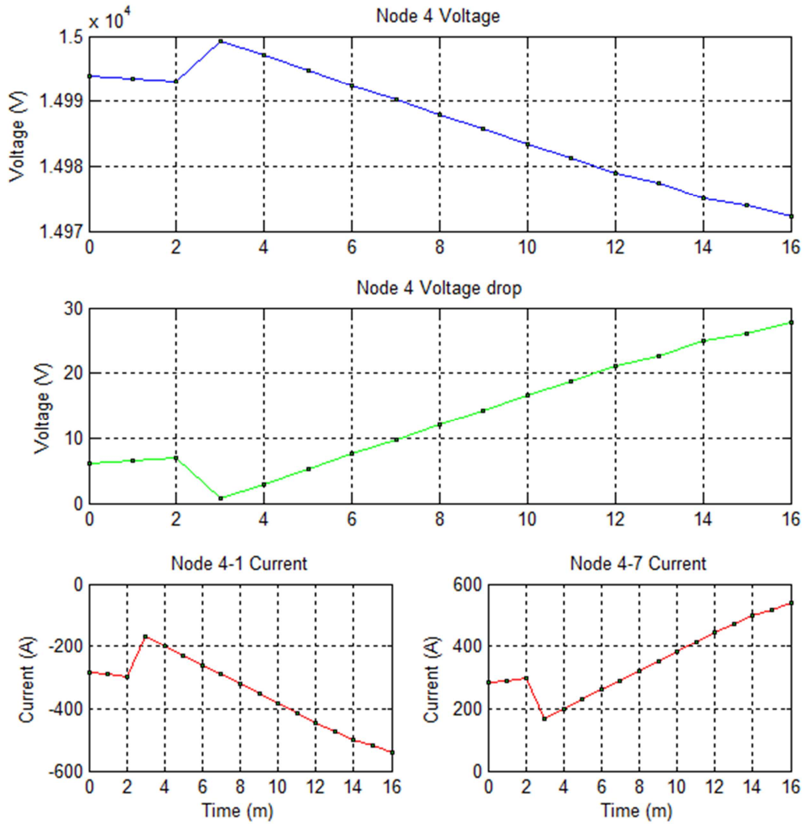
Annex 6 - Analysis of the Nodes 3, 4, 6, 7, 11

Node 3:



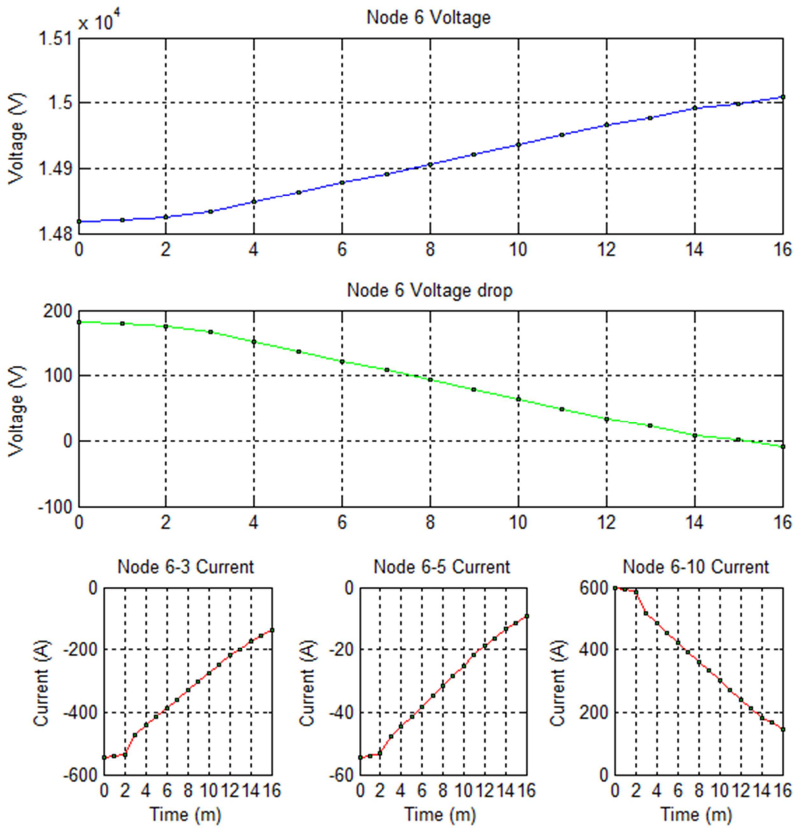
Node 3 Current											
Time	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
0	-543,17	0,00	0,00	0,00	0,00	543,17	0,00	0,00	0,00	0,00	0,00
1	-539,59	0,00	0,00	0,00	0,00	539,59	0,00	0,00	0,00	0,00	0,00
2	-532,84	0,00	0,00	0,00	0,00	532,84	0,00	0,00	0,00	0,00	0,00
3	-470,61	0,00	0,00	0,00	0,00	470,61	0,00	0,00	0,00	0,00	0,00
4	-442,67	0,00	0,00	0,00	0,00	442,67	0,00	0,00	0,00	0,00	0,00
5	-414,73	0,00	0,00	0,00	0,00	414,73	0,00	0,00	0,00	0,00	0,00
6	-386,78	0,00	0,00	0,00	0,00	386,78	0,00	0,00	0,00	0,00	0,00
7	-358,84	0,00	0,00	0,00	0,00	358,84	0,00	0,00	0,00	0,00	0,00
8	-330,90	0,00	0,00	0,00	0,00	330,90	0,00	0,00	0,00	0,00	0,00
9	-302,96	0,00	0,00	0,00	0,00	302,96	0,00	0,00	0,00	0,00	0,00
10	-275,01	0,00	0,00	0,00	0,00	275,01	0,00	0,00	0,00	0,00	0,00
11	-247,07	0,00	0,00	0,00	0,00	247,07	0,00	0,00	0,00	0,00	0,00
12	-219,13	0,00	0,00	0,00	0,00	219,13	0,00	0,00	0,00	0,00	0,00
13	-198,26	0,00	0,00	0,00	0,00	198,26	0,00	0,00	0,00	0,00	0,00
14	-170,32	0,00	0,00	0,00	0,00	170,32	0,00	0,00	0,00	0,00	0,00
15	-156,35	0,00	0,00	0,00	0,00	156,35	0,00	0,00	0,00	0,00	0,00
16	-136,83	0,00	0,00	0,00	0,00	136,83	0,00	0,00	0,00	0,00	0,00

Node 4:



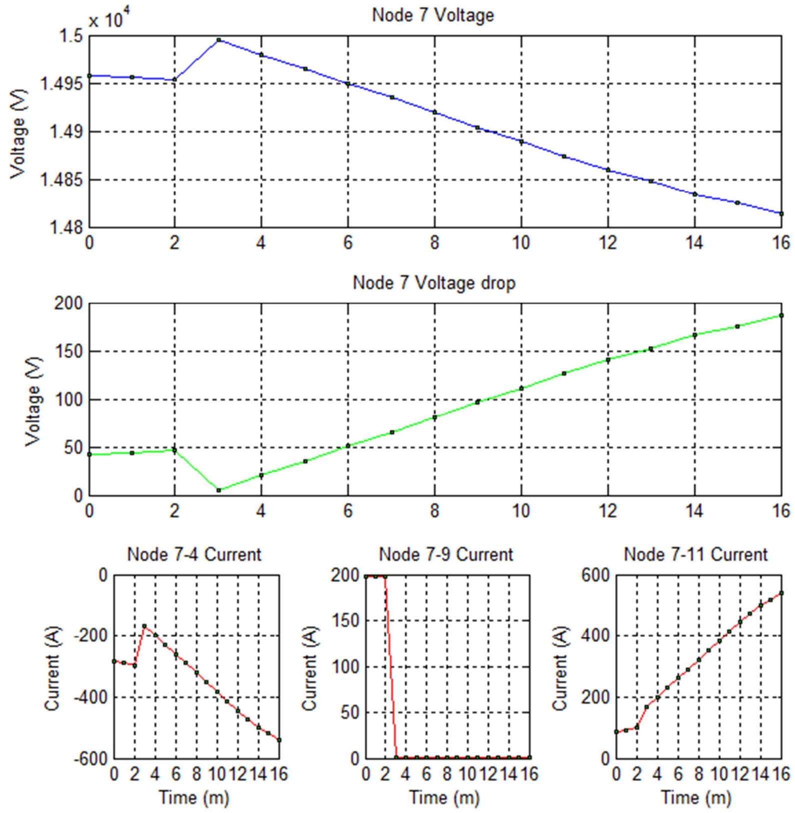
Node 4 Current											
Time	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
0	-284,34	0,00	0,00	0,00	0,00	0,00	284,34	0,00	0,00	0,00	0,00
1	-288,31	0,00	0,00	0,00	0,00	0,00	288,31	0,00	0,00	0,00	0,00
2	-295,84	0,00	0,00	0,00	0,00	0,00	295,84	0,00	0,00	0,00	0,00
3	-166,28	0,00	0,00	0,00	0,00	0,00	166,28	0,00	0,00	0,00	0,00
4	-197,47	0,00	0,00	0,00	0,00	0,00	197,47	0,00	0,00	0,00	0,00
5	-228,66	0,00	0,00	0,00	0,00	0,00	228,66	0,00	0,00	0,00	0,00
6	-259,85	0,00	0,00	0,00	0,00	0,00	259,85	0,00	0,00	0,00	0,00
7	-291,04	0,00	0,00	0,00	0,00	0,00	291,04	0,00	0,00	0,00	0,00
8	-322,23	0,00	0,00	0,00	0,00	0,00	322,23	0,00	0,00	0,00	0,00
9	-353,42	0,00	0,00	0,00	0,00	0,00	353,42	0,00	0,00	0,00	0,00
10	-384,61	0,00	0,00	0,00	0,00	0,00	384,61	0,00	0,00	0,00	0,00
11	-415,80	0,00	0,00	0,00	0,00	0,00	415,80	0,00	0,00	0,00	0,00
12	-446,99	0,00	0,00	0,00	0,00	0,00	446,99	0,00	0,00	0,00	0,00
13	-470,23	0,00	0,00	0,00	0,00	0,00	470,23	0,00	0,00	0,00	0,00
14	-501,42	0,00	0,00	0,00	0,00	0,00	501,42	0,00	0,00	0,00	0,00
15	-517,02	0,00	0,00	0,00	0,00	0,00	517,02	0,00	0,00	0,00	0,00
16	-538,86	0,00	0,00	0,00	0,00	0,00	538,86	0,00	0,00	0,00	0,00

Node 6:



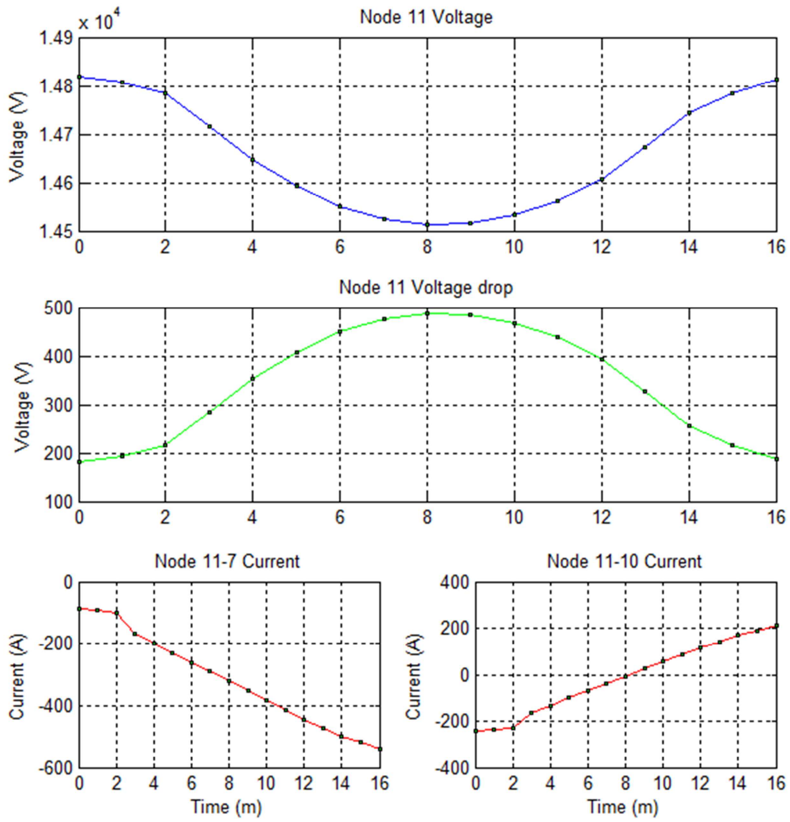
Node 6 Current											
Time	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
0	0,00	0,00	-543,17	0,00	-54,34	0,00	0,00	0,00	0,00	597,50	0,00
1	0,00	0,00	-539,59	0,00	-53,94	0,00	0,00	0,00	0,00	593,53	0,00
2	0,00	0,00	-532,84	0,00	-53,16	0,00	0,00	0,00	0,00	586,00	0,00
3	0,00	0,00	-470,61	0,00	-47,91	0,00	0,00	0,00	0,00	518,52	0,00
4	0,00	0,00	-442,67	0,00	-44,66	0,00	0,00	0,00	0,00	487,33	0,00
5	0,00	0,00	-414,73	0,00	-41,41	0,00	0,00	0,00	0,00	456,14	0,00
6	0,00	0,00	-386,78	0,00	-38,17	0,00	0,00	0,00	0,00	424,95	0,00
7	0,00	0,00	-358,84	0,00	-34,92	0,00	0,00	0,00	0,00	393,76	0,00
8	0,00	0,00	-330,90	0,00	-31,67	0,00	0,00	0,00	0,00	362,57	0,00
9	0,00	0,00	-302,96	0,00	-28,42	0,00	0,00	0,00	0,00	331,38	0,00
10	0,00	0,00	-275,01	0,00	-25,18	0,00	0,00	0,00	0,00	300,19	0,00
11	0,00	0,00	-247,07	0,00	-21,93	0,00	0,00	0,00	0,00	269,00	0,00
12	0,00	0,00	-219,13	0,00	-18,68	0,00	0,00	0,00	0,00	237,81	0,00
13	0,00	0,00	-198,26	0,00	-16,30	0,00	0,00	0,00	0,00	214,56	0,00
14	0,00	0,00	-170,32	0,00	-13,05	0,00	0,00	0,00	0,00	183,37	0,00
15	0,00	0,00	-156,35	0,00	-11,43	0,00	0,00	0,00	0,00	167,78	0,00
16	0,00	0,00	-136,83	0,00	-9,11	0,00	0,00	0,00	0,00	145,94	0,00

Node 7:



Node 7 Current											
Time	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
0	0,00	0,00	0,00	-284,34	0,00	0,00	0,00	0,00	197,13	0,00	87,21
1	0,00	0,00	0,00	-288,31	0,00	0,00	0,00	0,00	197,13	0,00	91,18
2	0,00	0,00	0,00	-295,84	0,00	0,00	0,00	0,00	197,13	0,00	98,72
3	0,00	0,00	0,00	-166,28	0,00	0,00	0,00	0,00	0,08	0,00	166,20
4	0,00	0,00	0,00	-197,47	0,00	0,00	0,00	0,00	0,08	0,00	197,39
5	0,00	0,00	0,00	-228,66	0,00	0,00	0,00	0,00	0,08	0,00	228,58
6	0,00	0,00	0,00	-259,85	0,00	0,00	0,00	0,00	0,08	0,00	259,77
7	0,00	0,00	0,00	-291,04	0,00	0,00	0,00	0,00	0,08	0,00	290,96
8	0,00	0,00	0,00	-322,23	0,00	0,00	0,00	0,00	0,08	0,00	322,15
9	0,00	0,00	0,00	-353,42	0,00	0,00	0,00	0,00	0,08	0,00	353,34
10	0,00	0,00	0,00	-384,61	0,00	0,00	0,00	0,00	0,08	0,00	384,53
11	0,00	0,00	0,00	-415,80	0,00	0,00	0,00	0,00	0,08	0,00	415,72
12	0,00	0,00	0,00	-446,99	0,00	0,00	0,00	0,00	0,08	0,00	446,91
13	0,00	0,00	0,00	-470,23	0,00	0,00	0,00	0,00	0,08	0,00	470,15
14	0,00	0,00	0,00	-501,42	0,00	0,00	0,00	0,00	0,08	0,00	501,34
15	0,00	0,00	0,00	-517,02	0,00	0,00	0,00	0,00	0,08	0,00	516,94
16	0,00	0,00	0,00	-538,86	0,00	0,00	0,00	0,00	0,08	0,00	538,78

Node 11:



Node 11 Current											
Time	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
0	0,00	0,00	0,00	0,00	0,00	0,00	-87,21	0,00	0,00	-241,78	0,00
1	0,00	0,00	0,00	0,00	0,00	0,00	-91,18	0,00	0,00	-237,81	0,00
2	0,00	0,00	0,00	0,00	0,00	0,00	-98,72	0,00	0,00	-230,28	0,00
3	0,00	0,00	0,00	0,00	0,00	0,00	-166,20	0,00	0,00	-162,79	0,00
4	0,00	0,00	0,00	0,00	0,00	0,00	-197,39	0,00	0,00	-131,60	0,00
5	0,00	0,00	0,00	0,00	0,00	0,00	-228,58	0,00	0,00	-100,41	0,00
6	0,00	0,00	0,00	0,00	0,00	0,00	-259,77	0,00	0,00	-69,22	0,00
7	0,00	0,00	0,00	0,00	0,00	0,00	-290,96	0,00	0,00	-38,03	0,00
8	0,00	0,00	0,00	0,00	0,00	0,00	-322,15	0,00	0,00	-6,84	0,00
9	0,00	0,00	0,00	0,00	0,00	0,00	-353,34	0,00	0,00	24,34	0,00
10	0,00	0,00	0,00	0,00	0,00	0,00	-384,53	0,00	0,00	55,53	0,00
11	0,00	0,00	0,00	0,00	0,00	0,00	-415,72	0,00	0,00	86,72	0,00
12	0,00	0,00	0,00	0,00	0,00	0,00	-446,91	0,00	0,00	117,91	0,00
13	0,00	0,00	0,00	0,00	0,00	0,00	-470,15	0,00	0,00	141,16	0,00
14	0,00	0,00	0,00	0,00	0,00	0,00	-501,34	0,00	0,00	172,35	0,00
15	0,00	0,00	0,00	0,00	0,00	0,00	-516,94	0,00	0,00	187,95	0,00
16	0,00	0,00	0,00	0,00	0,00	0,00	-538,78	0,00	0,00	209,79	0,00

Annex 7 - Power Flow Algorithm

- Network

```
function [nos,Y,B1,B2,carga]=rede1_RF(Vb,Zb,f)

%1-Generator
%2- Entrance SST1
%3- Entrance SST2
%4- Entrance SST3
%5- Output SST1 TRF1
%6- Output SST2 TRF2
%7- Output SST3 TRF3
%8-Catenarie
%9- Catenarie
%10- Catenarie
%11- Catenarie

nos=linspace(1,11,11)';

%Short-circuit power in the entrance of the  traction power substations

Scc1=1500e6;
Scc2=2500e6;
Scc3=2000e6;
Zcc1=j*Vb^2/Scc1;
Zcc2=j*Vb^2/Scc2;
Zcc3=j*Vb^2/Scc3;

%Transformers Impedance

Ucc=8/100;
Sn=14e6;
Ztrf11=j*((Ucc*Vb^2)/Sn)/2;
Ztrf22=j*((Ucc*Vb^2)/Sn)/2;
Ztrf33=j*((Ucc*Vb^2)/Sn)/2;

%Catenarie and Return Impedance per km

Zcat=0.068+j*(6.7665e-004)*2*pi*f;

%Lenght per node

km610=0.001;
km1011=0.02;
km711=26.78;
km79=0.92;
km58=0.001;
km65=73;

%Add the admittances in the busbars

Y=zeros(length(nos));
B1=zeros(length(nos));
```

```
%Superior matrix, simetric matrix

Y(1,1)=1/Zcc1+1/Zcc2+1/Zcc3;
Y(1,2)=-1/Zcc1;
Y(1,3)=-1/Zcc2;
Y(1,4)=-1/Zcc3;

B1(1,1)=1/imag(Zcc1)+1/imag(Zcc2)+1/imag(Zcc3);
B1(1,2)=-1/imag(Zcc1);
B1(1,3)=-1/imag(Zcc2);
B1(1,4)=-1/imag(Zcc3);

Y(2,2)=1/Zcc1+1/Ztrf11;
Y(2,5)=-1/Ztrf11;

B1(2,2)=1/imag(Zcc1)+1/imag(Ztrf11);
B1(2,5)=-1/imag(Ztrf11);

Y(3,3)=1/Zcc2+1/Ztrf22;
Y(3,6)=-1/Ztrf22;

B1(3,3)=1/imag(Zcc2)+1/imag(Ztrf22);
B1(3,6)=-1/imag(Ztrf22);

Y(4,4)=1/Zcc3+1/Ztrf33;
Y(4,7)=-1/(Ztrf33);

B1(4,4)=1/imag(Zcc3)+1/imag(Ztrf33);
B1(4,7)=-1/imag(Ztrf33);

Y(5,5)=1/Ztrf11+1/(Zcat*km58)+1/(Zcat*km65);
Y(5,8)=-1/(Zcat*km58);
Y(5,6)=-1/(Zcat*km65);

B1(5,5)=1/imag(Ztrf11)+1/imag(Zcat*km58)+1/imag(Zcat*km65);
B1(5,8)=-1/imag(Zcat*km58);
B1(5,6)=-1/imag(Zcat*km65);

Y(6,6)=1/Ztrf22+1/(Zcat*km65)+1/(Zcat*km610);
Y(6,10)=-1/(Zcat*km610);

B1(6,6)=1/imag(Ztrf22)+1/imag(Zcat*km65)+1/imag(Zcat*km610);
B1(6,10)=-1/imag(Zcat*km610);

Y(7,7)=1/Ztrf33+1/(Zcat*km711)+1/(Zcat*km79);
Y(7,9)=-1/(Zcat*km79);
Y(7,11)=-1/(Zcat*km711);

B1(7,7)=1/imag(Ztrf33)+1/imag(Zcat*km711)+1/imag(Zcat*km79);
B1(7,9)=-1/imag(Zcat*km79);
B1(7,11)=-1/imag(Zcat*km711);

Y(8,8)=1/(Zcat*km58);
B1(8,8)=1/imag(Zcat*km58);

Y(9,9)=1/(Zcat*km79);
B1(9,9)=1/imag(Zcat*km79);
```

```
Y(10,10)=1/(Zcat*km610)+1/(Zcat*km1011);
Y(10,11)=-1/(Zcat*km1011);

B1(10,10)=1/imag(Zcat*km610)+1/imag(Zcat*km1011);
B1(10,11)=-1/imag(Zcat*km1011);

Y(11,11)=1/(Zcat*km1011)+1/(Zcat*km711);
B1(11,11)=1/imag(Zcat*km1011)+1/imag(Zcat*km711);

%  (pu values)

Y=Y*Zb;
B1=B1*Zb;

%Inferior diagonal matrix, symmetric of the superior matrix

Y=Y+(conj(Y')-eye(length(nos)).*Y);
B1=B1+(B1'-eye(length(nos)).*B1);

%Matrix without the balance node

B1(1,:)=[];
B1(:,1)=[];
B2=-imag(Y(2:length(Y),2:length(Y)));

%Loads Characterization

carga(1).no=10;
carga(1).potencia=4.59;
carga(1).cosfi=0.93;

carga(2).no=11;
carga(2).potencia=4.07;
carga(2).cosfi=0.97;

carga(3).no=9;
carga(3).potencia=2.49;
carga(3).cosfi=0.95;
```

- Powerflow Algorithm

```
% POWERFLOW - Calcula o transito de potencia (Power Flow calculation)

clear

Vb=15*1e3;
Vnbpu=1;

Sb=14e6;
Zb=Vb^2/Sb;
f=16.7;

V=[];
S=[];
It=[];

[nos,Y,B1,B2,carga]=network_RF(Vb,Zb,f);

nnos=length(nos);
```

```
% Matriz das cargas, as potencias estao em MW e MVA (Load Matrix)

PQcomb(nnos,1)=0;
for n = 1:length(carga)
   fi=acos(carga(n).cosfi);
   P=carga(n).potencia*cos(fi);
   Q=carga(n).potencia*sin(fi);
   pno=find(carga(n).no == nos);
   PQcomb(pno)=PQcomb(pno)+(P+j*Q)*1e6;
end

% Matriz coluna das Potencias (Power Matrix)

PQger(1:nnos,1)=0;
PQger(1)=sum(PQcomb);
Pesp=real(PQger-PQcomb);
Qesp=imag(PQger-PQcomb);

%------------------------------------------------------------------------

%Quedas de tensão (Voltage Drop)

Yger=1/(0.54i);
Y(1,1)=Y(1,1)+Yger;
Z=inv(Y/Zb);

I=-conj((Pesp+j*Qesp)/(12000));

%[dV]=[Z]*[I] (Voltage Drop Calculation)
dV=Z*I;

Vnit=ones(nnos,1)*Vb-dV; (Voltage Calculation)

%------------------------------------------------------------------------

% Calculo das Potencia nos barramentos  (Power BusBar)

Y2=Y;
Vnit1=Vnit/Vb;

   for m = 1:nnos


      Snit(m,1)=conj(Vnit1(m))*Y2(m,:)*Vnit1;

   end

  S=-conj(Snit)*Sb; % (BusBar Power Calculation)

%------------------------------------------------------------------------

% Calculo da potencia de perdas  (Power Losses)

PPerdas(1:nnos,1)=0;
PPerdas=sum(S); % (Power Losses Calculation)


%------------------------------------------------------------------------
```

```
% Potência Transitada   (Power Flow Between Busbars)

for i = 1: nnos;

  for j = 1:nnos;

    A(i,j)=conj(Y2(i,j))*(((abs(Vnit1(i))^2)-(Vnit1(i)*conj(Vnit1(j)))));

  end
end

B=(A*Sb); %(Power Flow Calculation)

%--------------------------------------------------------------------------

%Calculo Comprimento maximo entre substações  (Maximum Lenght Between Substations)

km711=198.17;
km610=198.17;

AVmax=max(dV(:));
[num idx]=max(dV(:));
[l c] = ind2sub(size(dV),idx);

Per7_11=(0.068+(6.7665e-004*2*16.7*3.1415i))*km711

I7_11=real((Vnit(7,1)-Vnit(11,1))/(Per7_11))

Distmax=abs(2*(((3000))/(I7_11*(0.068+(6.7665e-004*2*16.7*3.14159265i)))))+km610  % (Maximum Lenght
Calculation)
```

Annex 8 - Aubepine Results vs Timetable

Secção Feeder: 26,78 Km	ΔUmax=13,39 Km			S-Start	A-Arrival	B-Station	L-Track		
Train BR 146 ●▶	Distance Betwen Trains:km	0,00	0,50	1,00	3,00	5,00	7,00	9,00	11,00
Train BR 101 ●▶		0,00	0,00	0,50	2,00	4,00	6,00	8,00	10,00
Minute		0	1	2	3	4	5	6	7
Train	Line								
01- ET 425	Ulm-Stutt	-	-	-	-	-	-	-	-
02- BR 146	Ulm-Stutt	S	L	L	L	L	L	L	L
03- BR 101	Ulm-Stutt	B	S	L	L	L	L	L	L
Number of Trains									
Departure		1	1						
Arrival									
Station		1							
Route			1	11	11	11	11	11	11
Number of Trains									
Acceleration		1	1		1	1		1	
Brake									1
Stop		1							
Constant Velocity			1	11	1	1	11	1	1
Consumption MW									
Acceleration		3,856956	5,439073		5,4390732	3,856956		5,439073	
Brake									-2,31778
Stop									
Constant Velocity			1,069263	2,406072	1,0692631	1,33	2,406072374	1,069263	1,336809
SUM: Consumption MW		3,856956	6,508336	2,406072	6,5083364	5,186956	2,406072374		-0,98097
Extra Charge (6 MW)			E	EE	E	E	EE	E	E
SUM: Consumption with Extra Charge (6 MW)		3,856956	12,50834	14,43643	11,854652	11,83696	14,43643425	11,85465	5,019032

E: Extra charge 1 train in the sector EE: Extra charge 2 trains in the sector

13,00	15,00	17,00	19,00	21,00	23,00	25,00	26,00	26,78
12,00	14,00	16,00	18,00	20,00	21,00	23,00	24,00	26,00
8	9	10	11	12	13	14	15	16
-	-	-	-	-	-	-	-	-
L	L	L	L	L	L	L	L	A
L	L	L	L	L	L	L	L	L
								1
11	11	11	11	11	11	11	11	1
11	11	1					1	
								1
		1	11	11	11	11	1	1
-4,22707	-4,22707	-1,91					-2,31778	
								0
		1,069263	2,406072	2,406072	2,406072	2,406072	1,336809	1,336809
-4,22707	-4,22707	4,505579	2,406072	2,406072	2,406072	2,406072	-0,98097	1,336809
		E	EE	EE	EE	EE	E	
-4,22707	-4,22707	5,574842	14,43643	14,40607	14,43643	14,43643	5,703078	1,336809

ANOTHER SECTION

26,78	27,35	27,78
	●▶ET 425	
0	1	2
S	L	L
1		
	1	1
1		
		1
	1	
2,25		
		-1,275
	0,513	
2,25	0,513	-1,275
	E	
2,25	6,513	-1,275

750 Ulm - Geislingen (Steige) - Göppingen - Stuttgart *Filstalbahn* ← 750

Von Ulm Hbf bis Amstetten Verbundtarif Donau-Iller-Nahverkehrsverbund (DING) R4
Von Reichenbach (Fils) bis Stuttgart Hbf Verbundtarif Verkehrs- und Tarifverbund Stuttgart (VVS) S1 R1

Von Geislingen (Steige) bis Ebersbach (Fils) Verbundtarif Filsland Mobilitätsverbund

Zug	CNL 40418	IC 60418	CNL 418	CNL 1318	ICE 618	RB 19296	ICE 616	RB 19298	S1 7825	RB 19300	RB 19302	RE 19200	RB 19302	RB 19306	RE 19202	IC 2268
	R 2.	2.	R	R	Mo 32			Mo-Fr 3	Mo-Fr 3		Mo-Fr 3	Mo-Fr 3	Mo-Fr 3	Mo-Fr 3	Sa,So 8	Mo-Fr 3
			30	31												
von	München Hbf	München Hbf	München Hbf	Innsbruck Hbf	München Hbf		München Hbf									München Hbf
Ulm Hbf *(478 m)* 751, 755, 757, 980	010	010	010	010	202	411	440			455		523		533	601	602
Beimerstetten										504				542		
Westerstetten										509		535		547		
Lonsee										512		539		551		
Urspring										515				554		
Amstetten (Württ) 758						428				519		546		558	618	
Geislingen (Steige) *(469 m)* 3 ○		033				434				525		553		605	624	623
Geislingen (Steige)	034	034	034	034		435				525	543	554		606	625	625
Geislingen (Steige) West										529	547			611		
Kuchen						440				532	549			614		
Gingen (Fils)						443				535	552			618		
Süßen ○						446				537	555	602		621	633	
Süßen						447		521		538	556	603		622	633	
Salach						449		523		541	558			625	→	
Eislingen (Fils)						452		526		544	601			628		
Göppingen 3 ○		047				456		529		547	605	609		632		637
Göppingen	048	048	048	048		457		530		548	613	609	613	652		639
Faurndau						500		533		551	→		616	→		
Uhingen						503		536		554			619			
Ebersbach (Fils)						508		540		558		616	623			
Reichenbach (Fils)						512		544		602			627			
Plochingen 760 4 ○		100				517		548		606		622	631			649
Plochingen S 60	102	102	102	102		518			553	607		623	635			651
Esslingen (Neckar) S 3 ○						525			603	613		629	641			
S-Bad Cannstatt S 785, 790.2-3 3 ○						533			615	621		638	648			
Stuttgart Hbf (tief) S 790.4-5, 790.6 90 3									620							
Stuttgart Hbf *(247 m)* ✈ 60 7 ○		116			300	538	537			626		643	653			707
nach	Paris Est		Amsterdam	Amsterdam	Essen Hbf		Dortmund Hbf		Herrenberg					Mosbach-Neckarelz		Karlsruhe Hbf

Zug	RE 19202	RE 19204	RB 19306	RB 19310	RB 19270	ICE 614	IRE 4240	IRE 4220	IC 2294	RB 19312	RE 19206	RB 19314	RB 19316	RB 19272	TGV 9576	TGV 9576
	Sa,So 8	Mo-Fr 3	Mo-Fr 3	Mo-Fr 3	Mo-Fr 3		Mo-Fr 3	Sa,So 8	Mo-Fr 33	Mo-Fr 3	Mo-Fr 3	Mo-Fr 3	Sa,So 8	Mo-Fr 3	Mo-Fr 3	34
von						München Hbf	Friedrichs-hfn. Stadt	Friedrichs-hfn. Stadt	München Hbf						München Hbf	München Hbf
Ulm Hbf *(478 m)* 751, 755, 757, 980		607		613	630	651	654	654	659		706		710	727	742	742
Beimerstetten				621	639								718	735		
Westerstetten				626	643								722	740		
Lonsee				630	647						719		726	744		
Urspring				633	650						722		728	746		
Amstetten (Württ) 758		624		636	654						726		731	750		
Geislingen (Steige) *(469 m)* 3 ○		630		642	700		716	716	721		732		737	756		
Geislingen (Steige)		631		643			717	717	722		732	737	738			
Geislingen (Steige) West				647							736	741	742			
Kuchen				649								743	744			
Gingen (Fils)				652								746	747			
Süßen ○		639		655							741	748	750			
Süßen	633	639		656						731	742	749	750			
Salach				659						733		751	752			
Eislingen (Fils)	638	644		702						736	746	754	755			
Göppingen 3 ○	642	648		706			728	728		740	749	757	758			
Göppingen	643	649	652	707			729	729		740	751	758	758			
Faurndau	647		655							743		801	801			
Uhingen	650		658							746		804	804			
Ebersbach (Fils)	654	656	702							750	757	808	807			
Reichenbach (Fils)	659		707	716						754		812	811			
Plochingen 760 4 ○	703	703	711	720				739	744	759	803	816	815			
Plochingen S 60	705	705	711	722				740	746		805	816	815			
Esslingen (Neckar) S 3 ○	711	711	718								811	823	821			
S-Bad Cannstatt S 785, 790.2-3 3 ○	719	718	727								819	829	828			
Stuttgart Hbf (tief) S 790.4-5, 790.6 90 3																
Stuttgart Hbf *(247 m)* ✈ 60 7 ○	724	724	732	738		747	756	756	801		824	835	832		839	842
nach			Mosbach-Neckarelz			Dortmund Hbf			Frankfurt (M)Hbf		Mosbach-Neckarelz				Paris Est	Paris Est

3 nicht 26. Dez, 6. Jan, 6., 9. Apr, 1., 17., 28. Mai, 7. Jun, 3. Okt, 1. Nov
8 auch 26. Dez, 6. Jan, 6., 9. Apr, 1., 17., 28. Mai, 7. Jun, 3. Okt, 1. Nov
30 12. Dez bis 14. Apr Mo - Sa; 16. Apr bis 8. Dez
31 11. Dez bis 15. Apr So
32 nicht 26. Dez, 9. Apr, 28. Mai; auch 27. Dez, 10. Apr, 29. Mai
33 nicht 26. Dez, 6., 9. Apr, 17., 28. Mai, 7. Jun
34 6. Jan, 1., 17. Mai, 7. Jun, 3. Okt, 1. Nov
60 Gesamtverkehr siehe 790.1
90 Umstieg nach Hbf oben 9 Minuten

CNL 418 **POLLUX**
CNL 1318 **POLLUX**
CNL 40418 **CASSIOPEIA**
IRE 4240 **IRE-SPRINTER**