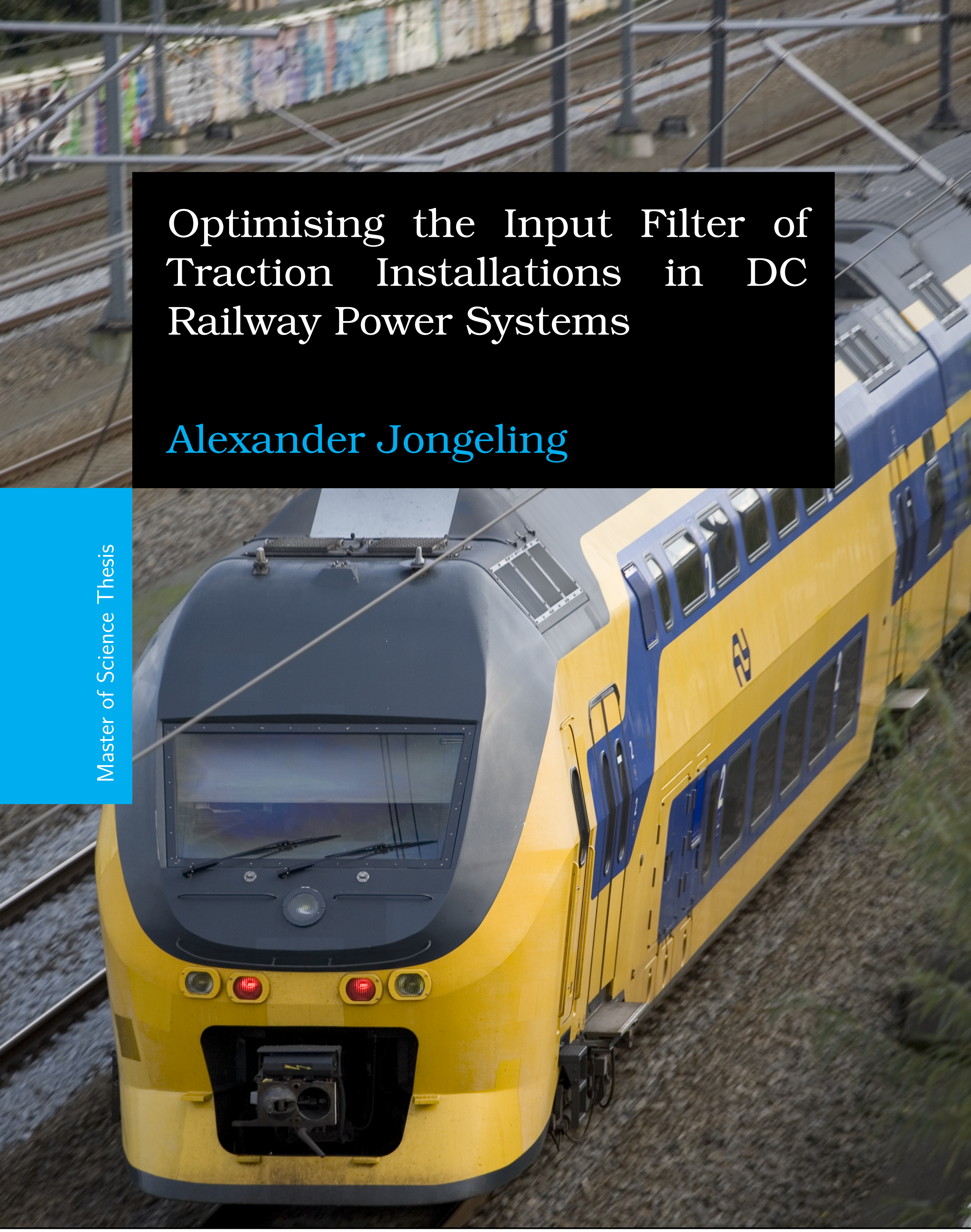

Optimising the Input Filter of Traction Installations in DC Railway Power Systems

Alexander Jongeling

Master of Science Thesis

TU Delft Delft University of Technology

DC systems, Energy conversion & Storage

Optimising the Input Filter of Traction Installations in DC Railway Power Systems

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI) for acceptance a thesis entitled

Optimising the Input Filter of Traction Installations in DC Railway Power Systems

by

Alexander Jongeling

in partial fulfillment of the requirements for the degree of

Master of Science Electrical Power Engineering

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Abstract

In the world of DC railway trains nowadays, asynchronous-traction machine with traction controllers, i.e. an inverter with variable output frequency, is implemented. This controller changes the incoming DC voltage into an AC voltage of a variable frequency and RMS amplitude. The disadvantages of switching inverters, compared to a pure sine wave source, are the harmonics they inject in both the output as in the input of the inverters connection. At the incoming power line, it is necessary to damp these harmonics, in order to avoid resonance issues or issues regarding other systems, for instance, train detection. For this purpose of harmonic and transient filtering, generated within as well as outside the train, an LC filter is utilised. However, this LC-filter has also influence on stability. Due to the resulting impedance to current variation in the inductance of the LC-filter, the power flow dynamics towards the train are decreased. When applying a certain amount of power, the voltage over the capacitance can become unstable very quickly. In this thesis, a graphical user interface simulation model is made to simulate these stability phenomena in Simulink in order to find the optimum size of the LC-filter in a train on the Dutch DC railway.

The simulations are achieved with a model representing a generalised train. The model is simple to modify, and consists of the important parts for determining the stability of the system.

Different simulations have been carried out, in order to examine the effect certain parameter variations have on the stability. Two systems have been considered, a constant power controlled system and a system where the motors had no controlling regime. An important factor is the value of the capacitance and inductance. A larger filter inductor results in an unstable system. Likewise, implementing a higher value capacitance will cause the system to be more stable. Simulations have shown that a motor controller with a simple constant power control regime is unstable with normal values for the inductance and capacitance. However a damping branch can solve this problem up to an extent. A system without any controlling regime has proven to be more stable with smaller capacitance.

By utilising the model presented in this thesis, the stability of the system, consisting purely of a controlled constant power load or as a non-controlled load, can be investigated, and the impact of the LC-filter can be determined.

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During the 8 months I worked at Ricardo Rail, I had a great time with nice colleagues. It was always pleasant to be at the office and have a chat with them. All of the colleagues were available to assist me with the research. Thank you all for the support and the great times.

I want to thank, Mladen Gagić and Aniel Shri, for being my TU faculty supervisor. They have assist me during the entire thesis with writing, English proving and giving shape to my research.

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Delft, 6th July 2017

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Chapter 1

Introduction

1-1 Challenges of the railway in the Netherlands

The railway infrastructure in the Netherlands is highly utilised. In 2015 more then 3.3 million train trips have been made. On average over 1 million travellers per day are carried along with numerous freight trains along the rail network [7]. Utilisation of the railway infrastructure is today, apart from biking and walking, the most sustainable way of travelling[8]. It requires less space than other forms of transport, and has a positive impact on accessibility and mobility[8].

The president of ProRail, the company that manages most of the Dutch railway infrastructure, stated that in the future, more trains will operate on the same infrastructure, and those trains will be required to arrive and depart at a shorter time frame from each other[9]. He also wishes to increase the voltage on the railway overhead line[10] in order to allow for more trains and enable them accelerate faster.

Trains require adequate torque, in order to accelerate, decelerate or maintain a constant speed. In most of the Dutch trains, electric motors are driving the wheels. Likewise, in DC-fed trains two variants of traction systems are most often implemented. Traction via DC motors (with choppers or with switching series-resistance), which is being phased-out at the moment and asynchronous squirrel-cage traction motors driven by inverters. This asynchronous motor is relatively low in cost, offers high reliability and efficiency while achieving low maintenance requirements[11]. Next to that, the asynchronous motor is inherently less complex and more rugged in comparison than a DC traction motor[12].

However, an asynchronous traction motor requires a traction controller, i.e. an inverter with variable output frequency, to operate at the desired rate of torque and power. This controller will transform the incoming DC into AC with a variable frequency and RMS amplitude. This controller is also referred to as a switching inverter. The disadvantages of switching inverters, compared to a pure sine wave source, are the harmonics they inject in both the output as input of the inverters connection. At the incoming power line, these harmonics are required to be filtered in order to avoid current interference issues or issues with other systems, for example train detection[13]. On the output these harmonics must be properly damped, in order not to decrease the lifetime of the motor[14].

One should take care that the frequency of these harmonics are outside the frequency bands of rules and regulations, and that they do not interfere with other systems, in order to avoid instability or safety issues. This is due to the fact, that when the resonance frequency of a, for example LC-filter is subjected with another component generating currents/voltages at that specific frequency, the component in question will experience resonance oscillations.

A filter is therefore required, due to the distance between substation and train. This filter consists of a series inductance with a parallel capacitance. It is implemented to filter harmonics from the incoming overhead line, and to prevent harmonics, generated within the train to enter the overhead line. Likewise, it stores a certain amount of electrical energy within its inductance and capacitance. The inductance energy storage allows for non-disruptive current flow, in the pantograph when the overhead line is temporarily interrupted. But the filter also has several notable disadvantages, among which is its weight. It is also defined by a resonance frequency, that can be a cause of instability.

The inductance is very heavy because of the high current values that it is required to handle. A lower inductance could be beneficial to the overall weight of the train, considering an inductor could in practice, regularly weight up-to 800 kg[15]. However, the inductance is needed to filter the incoming and outgoing noise and to store energy.

The resonance frequency, eigen frequency, of the input LC-filter, is determined by the value of its inductance and capacitance and also the inductance value resulting from the overhead line. The varying distance from substation to train causes the total inductance to be of a variable nature. The bandwidth wherein this frequency is permitted to propagate, may be limited, in order not to overlap with other utilised frequencies. To ensure a higher resonance frequency, one should choose a low value capacitor. However, a smaller capacitor can cause traction control instability, when using a constant power control [16]. The biggest challenge to make a stable system, is the constant power control of the traction converter. By always requiring a constant power at the output of the motor, this control can cause system instability in a short time, by asking more current when voltage is decreasing, decreasing the voltage even further and vice versa.

In this thesis, a graphical user interface simulation model is made to simulate these stability phenomena in Simulink in order to find the optimum size of the LC-filter in a train on the Dutch DC railway. Investigations will be carried-out with respect to the sizing of the LC filter when combined with a perfect constant power load. The model parameters will be modified and the simulation results will be presented. In order to eliminate the effects of the constant power load, a second approach to this problem will be presented. In this approach, the constant power control is omitted from the system and a fixed frequency and voltage is placed onto the motors. Then the stability of the system is once again investigated.

The thesis starts in chapter 2 with an explanation about the structure of the DC railway system. In chapter 3 this system is made into a simulation model. After that the system is being validated in chapter 4. In chapters 5, 6 and 7 the simulations and results are discussed.

1-2 Thesis outline

1-2-1 Goal

The goal of this thesis is to gain an understanding into the influence of the input filter on stability and harmonics by simulation with a valid electrical model of traction installations in DC railway power systems.

1-2-2 Main objective

The main objective is to determine how the value of the filter capacitor and inductor (which are situated directly behind the pantograph) influence the stability of traction installations in DC railway power systems?

1-2-3 Sub objective

In order to answer the main question, the following sub-questions have been formulated.

1. How are currently existing traction installations designed, and what behaviour do they exhibit in current operation?
2. To what extent does the LC input filter have on stability of the system?
3. Which influence does the filter have on harmonic currents?
4. To which degree does the variation of filter and line parameters, influence the system stability

1-2-4 Scope of the thesis

In this thesis, a model of the current DC railway in the Netherlands, and a typical train will be created and presented. The idea is that the typical train model can be easily adapted to any particular train, and simulated on a model of the Dutch DC railway. Therefore, this thesis focuses on a general model, not specialised to a specific train. **The values implemented in this thesis, except for the validation chapter, are not intended to represent any particular train, nor should they be inferred as such.** The AC (25kV 50Hz) railway in the Netherlands, for example the HSL (high speed line), will not be covered by this model. The models scope includes every part of the system between the AC side of the substation and the wheels of the train, everything outside of this scope will be excluded from influencing the system.

The model will be designed in a simulation program, which will be chosen during the corresponding phase of the study.

1-3 Model

1-3-1 Requirements

The model has the following requirements:

- The model should be easily modifiable to represent a different train.
- Simulation on this model should not exceed 60 minutes, on the PC used to make the model. Wherein it should simulate a simulation time of at least 20 seconds.
- The output of the simulation should consist of, at least, the power and torque on the wheels, voltage on multiple important points, and the speed of the train relative to the ground.

1-3-2 Boundaries

System boundaries

- In this research only system parts between the AC/DC substation and the trains motors will be taken into account
- The 1500V ProRail (operator of the Dutch railway) situation is taken into account.

Content of the system

- Multiple trains, that are connected in parallel via the overhead line, are considered.
- Both single and double rail configurations should be investigated.

Modelling and simulation

- A general model, not specific of any particular train, will be implemented.
- The traction controller, will be a standard controller available in the simulation program.

Validation

- A validation of the model will be carried-out via simulation of a specific train. The choice of train dependent on parameters availability
- Simulation results based on the model will be compared to available measurements from that specific train
- No actual measurement on a train will be performed during this research.

1-4 Literature study

In this section a segment of the literature study that could not be included into a corresponding chapter in the report is discussed. More literature used in this research can be found at the corresponding locations within the thesis, mainly in chapter 2.

1-4-1 Inverting DC traction substations

A new type of a traction substation is proposed in [17]. It can feed energy back into the grid in the case of excessive regenerative power generation, however, it can also act as a dynamic power filter. In the late seventies, a reversible substation was successfully placed in Japan and a 8% energy saving was reached. However the thyristor controlled inverters were problematic. They had commutation problems and large circulating currents between rectifier and inverter were present. Therefore, a new design is proposed in [17]. In summary, this idea of using the energy of the harmonics or resonance and injecting it back into the grid or storing it into a capacitance can be beneficial for the overall stability of the voltage. However, the voltage range wherein recuperation is possible is limited, making it, because of the voltage drop on the overhead line, difficult to put a lot of power back into the mains. This idea is not considered in this thesis because the infrastructure is assumed to be fixed.

1-4-2 Active methods for stabilisation of LC input filters and DC/DC converters

When confronted with a long distance between an energy source and point-of-load, large input filters are required for noise reduction. These input filters, normally of LC type, interact with the constant power load and represent the dominant instability issue[18].

Using a feedforward loop in the motor controller control structure, the inverters impedance can be altered virtually around the resonance frequency of the LC-filter. With this the system can be made stable[18].

1-4-3 Maximum amount of power for a stable constant power controller

In the report about "Stability Criteria for Constant Power Loads With Multistage LC Filters" [19] the maximum amount of power that a constant power controlled load can take out of a network is limited by the voltage (V), resistance (R), capacitance (C) and inductance (L). The formula for stable power, in a constant power controlled loaded system, is:[19]

$$P < U^2 \cdot \frac{R \cdot C}{L} \tag{1-1}$$

When the power is less than the formula here above, then the system will be stable. If more power is taken from the network, the system can become unstable very quickly. Putting power back into the network, will have a stabilising effect on the system. The solution for the instability problem is to slow down the control of the duty cycle of the controller.

Chapter 2

The DC Railway System

In this chapter the different segments of the DC railway system are discussed. First, a global schematic is given, after that every segment of the system is discussed separately.

2-1 Overview

A schematic overview of the DC railway system can be found in figure 2-1. In this figure, subsystems that should be considered can be seen in the blocks. These subsystems will be considered and given each its own modular simulation block later in this thesis. Note that only one train is depicted here however multiple trains at close distances from each other will have to be simulated later in the thesis.

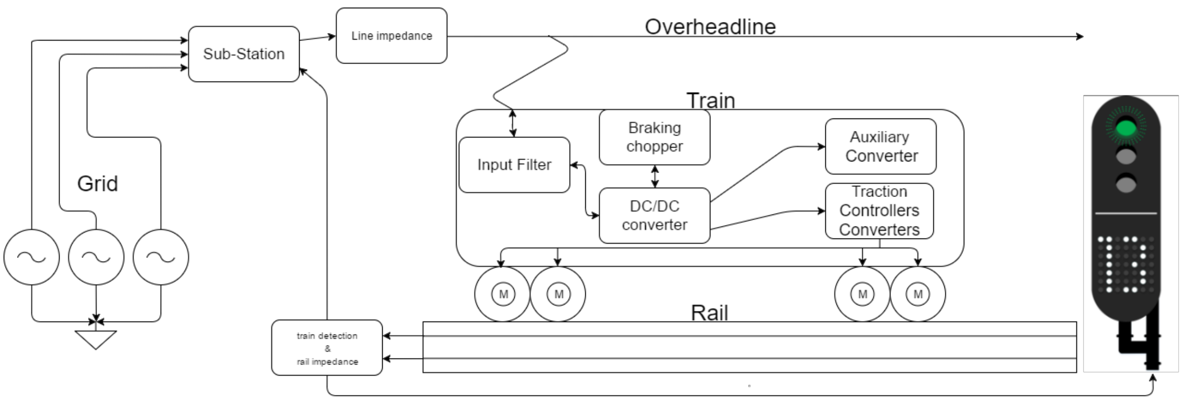

Figure 2-1: Block diagram overview of the system under research, signaling sign from [1]

2-2 Influencing factors in system stability

The following factors are the most important factors influencing the system stability. At least these factors should be considered:

- The LC-filter in the train.
- The variable inductance and resistance of the variable length overhead line and rail.
- Harmonics generated at the rectifier in the substation, including harmonics caused by imbalanced grid.
- The constant power control controllers.

2-3 General model Assumptions

- The AC grid supplying the substation is assumed stable, it has no voltage dips, flicker, external generated harmonics and/or transients and is simulated as a perfect voltage source. However voltage imbalance between phases will be researched as a fixed factor changing the voltage on only one phase.
- The motor controller is controlled by requested amount of torque at the wheels and works with the principle of constant power control. The torque controller controls the maximum amount of torque according to the voltage on the pantograph.
- Multiple trains may operate on the same line and same network.
- A train consist of multiple motors and converters.
- Fixed parameters are assumed constant in time and temperature.
- The infrastructure systems are fixed and cannot be changed.
- Only passive input filter can be used.
- Inverters are fed by the voltage coming from the pantograph and LC-filter. No DC/DC converter will be used in the DC railway model.

2-4 The rail infrastructure

2-4-1 Substation

The first system of the electrified train that has been investigated is the substation. Here the incoming AC power is transformed to 1800 V DC power that is being put onto the overhead line to feed the trains with electric energy. Note that the system is normally named 1500 V DC however the no-load voltage is normally 1800 V. The network used to have a 1500 V DC voltage on average in history. In the substations multiple rectifier configurations can be used. Many substations use a semi-12 pulse or 12 pulse converter (figure 2-3), only a few substations have a 6 pulse rectifier nowadays (figure 2-2). Also semi-24 pulse rectifiers are being used. The higher the amount of pulse, the higher the harmonic frequency of the converter is and the lower the distortion of the DC output is. Higher frequencies are easier and cheaper to filter, and causes less problems such as increasing the total harmonic distortion (THD) in the AC network, so a high pulse number is desired. Next to that a higher amount of pulses may be necessary to comply with the grid regulations, which can state that harmonics content in the current should be limited. Semi in front of the amount of pulses, means that the transformers secondary windings are not all on the same iron core. So multiple transformers with each its own iron core have been used when talking about semi. The advantage of this semi system is that it has a higher redundancy, the amount of pulses can fall back when one of the transformers is defect.

With a 6 pulse rectifier (figure 2-2) harmonics are generated at multiples of the 6th harmonic. The six pulse rectifier only uses a simple transformer and 6 diodes. The 12 pulse converter uses 12 diodes and two different transformer (wye and delta) topologies in order to avoid the 6th harmonics [20][21]. In that way the 12 pulse converter only has harmonics on multiples of the 12th harmonic. In the Dutch railway the 2 groups of 6 pulse converters are placed in parallel instead of series so that the maximum current output, not the voltage, is doubled. The 24 pulse rectifier uses also a zigzag transformer in front of the 2 separate wye and delta transformers to add or subtract an extra 7.5°of phase-shift (figure 2-4). Therefore it has only harmonics at the multiples of the 24th harmonic.

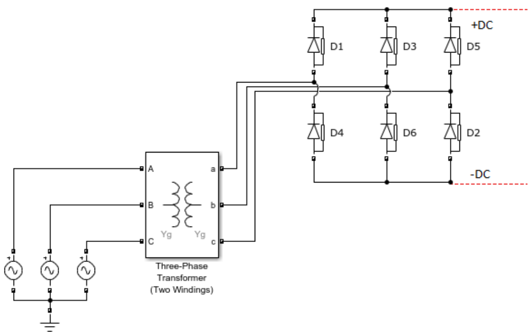

Figure 2-2: 6 pulse rectifier

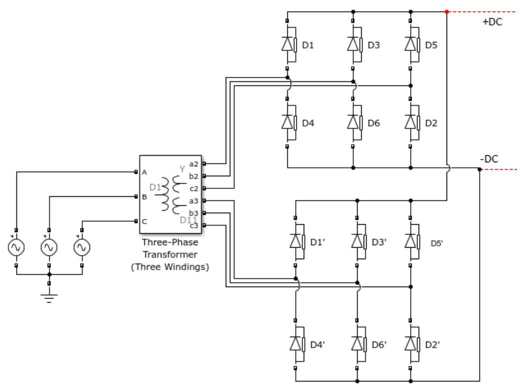

Figure 2-3: 12 pulse rectifier

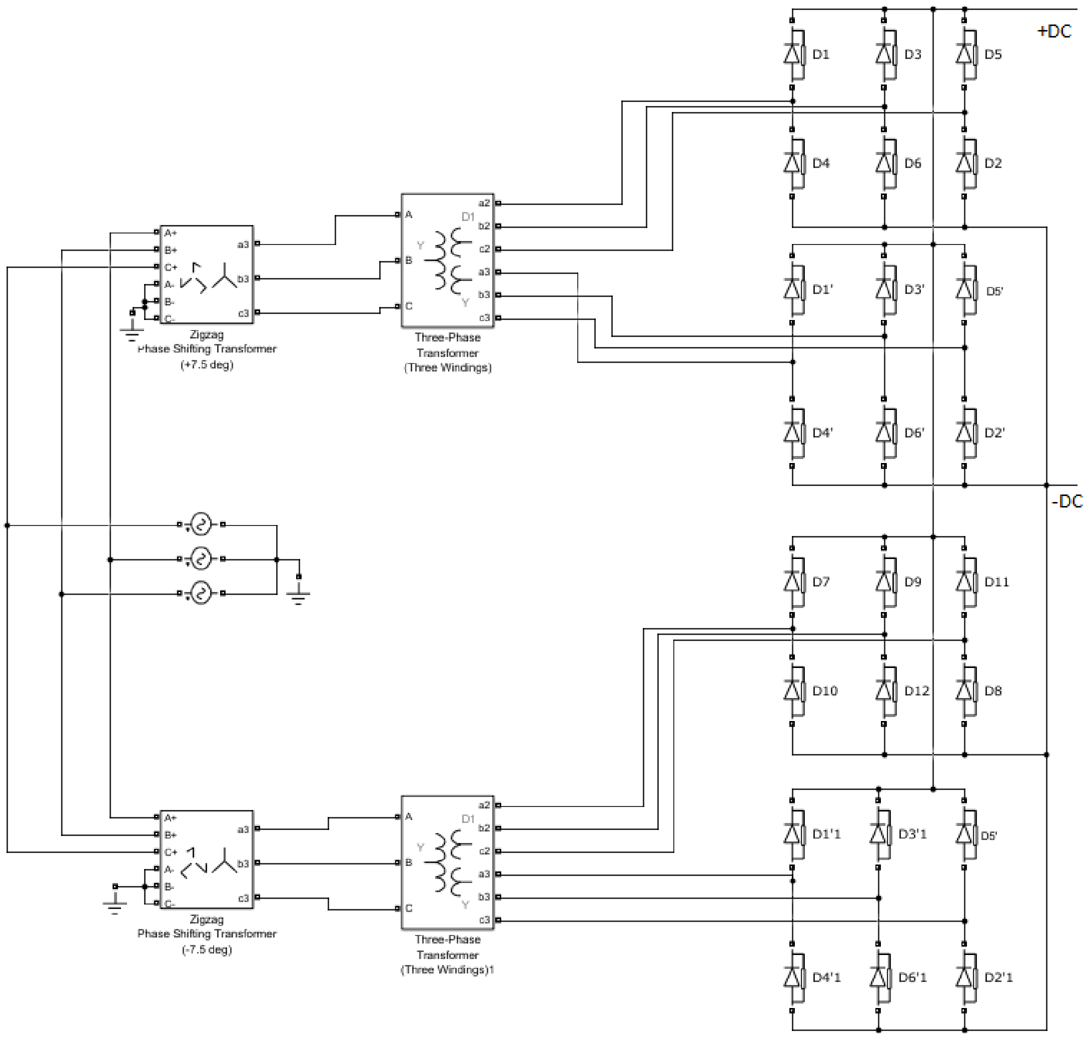

Figure 2-4: 24 pulse rectifier

Next to the harmonics generated when rectifying the AC to DC also harmonics are generated when the grid is in imbalance. Meaning that when loading is not in balance between the phases a harmonic at multiples of two times the supplying AC frequency exist in the DC output. A capacitor is present at the substations DC output with a typical value of $C = 100\mu F$[22]. This capacitor is however not implemented because of reasons which will be explained later in the thesis.

2-4-2 Variable length overhead line

To deliver energy to the train a supply line is needed. The overhead line carries the 1500 V DC and is connected to the train by a pantograph. This line from substation to pantograph consists of multiple parallel copper lines, thereby decreasing inductance and resistance. The overhead line can be seen as a series connection of an inductance and a resistance with parallel some capacitance. In appendix B it can be found that the capacitance from overhead line to ground is too small to store significant energy.

When simulating the effects of having a Pi section, with the line capacitance included, against a situation with the capacitance omitted one can see only an extremely small effect in the resonance frequency. The model used for this simulation can be seen in appendix B figure B-1. In appendix B figure B-2 the results after hundreds of oscillation cycles can be seen. Because this capacitance has such a limited effect on the oscillation frequency and the distance from overhead line to ground is too large to store significant energy at this voltage level it will be neglected in further study.

The impedance of the overhead line depends on many factors, like the amount of reinforcementcables, thickness of the cable etc. The following typical values have been used in this thesis:

- $R = 40m\Omega/km$
- $L = 2.0mH/km$

The equivalent scheme of the overhead line without the capacitance can be found in figure 2-5. The overhead line from substation to train is normally limited to approximate 10 km and can be as small as zero km. A consequence of this variability is that the parameters of the R and L are variable with the distance. In combination with the LC filter this variability makes the resonance frequency of the overhead line and LC filter also variable, giving rise to resonance problems when not dealt with them properly.

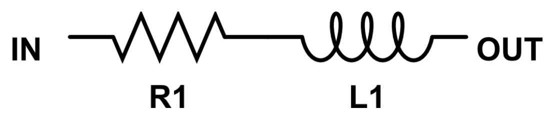

Figure 2-5: Equivalent scheme of overhead line without line capacitance

2-4-3 Surge Arrester

In close approximation of the substation and on the roof of the train surge arresters are placed. The function of this device is to divert the currents from high voltages away from the substation. These high voltages can be caused by lighting strikes and transients. A typical 1800 V system voltage version has a rating of 2100V, but it starts to conduct at far higher voltages. Because of that reason the component can not be used to dissipate the energy in a resonance oscillation. Protection systems will already have switched off the cause of the oscillation, before the voltage can get to a point where the surge arrester will become conductive. With that in mind it is not useful to include the surge arresters in this study.

2-4-4 Train detection system

The train detection systems are used to know whether or not a train is currently on the detection systems section. When a section is occupied, incoming trains should be stopped before arriving at the occupied section. The following train detection systems are being used nowadays:

- Track circuit
- Axle counter
- Treadles (switches)

2-4-5 Track circuit

In the track not only the DC return current but also the harmonics, transients and the automatic train control currents will flow. The automatic train control (a system that can intervene with the train driver to perform an emergency stop, and shows maximum speed to the driver) and train track detection currents works with alternating currents at 75 Hz. A maximum speed code is sampled on a 75 Hz signal and this signal is shorted through the wheels of the train. The current flowing through these wheels can be sensed by using a current sensor in front of the train wheels. This information can then be translated back to a speed code that limits the maximum speed of the train.

A simplified version of the track circuit system can be found in figure 2-6. A 75 Hz signal is placed on the track. At the end of the track a special 75 Hz relay is placed that is in normal conditions energised by the 75 Hz signal, consequently giving green light meaning the track is not occupied. When a train is on the track, the track lines are shorted together by the trains wheels and axle. At this moment there is no signal present anymore at the end of the track where the relay is. So the relay falls off. Now the green light turns off and the red light turns on, meaning there is a train on the tracks. This system is fault-save because when a track line is broken, the voltage is not present anymore at the relay connections, thereby giving a red light. When the relay is broken it will also fall off, meaning a red light. However when a train is injecting current of 75 Hz into the track circuits it could be possible to energise the relay again, giving green light when it should be red. This condition should be avoided at all times. A graphical overview of how the signalling works can be found in figure 2-7.

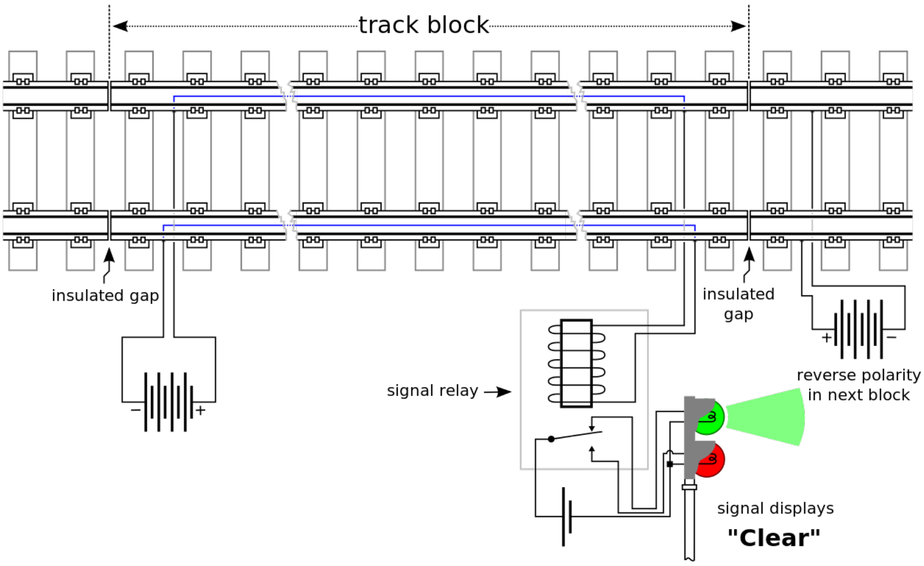

Figure 2-6: Double track circuit diagram [2]

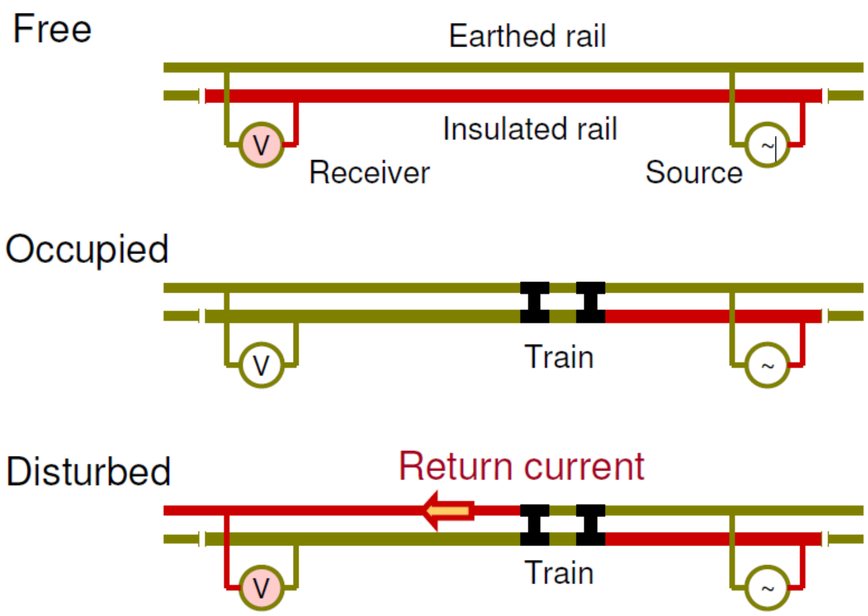

Figure 2-7: Overview of the single track ciruits [3]

Two sorts of tracks exist today, double and single isolated tracks. In double isolated tracks the return current flows through both tracks where in a single isolated system one track is reserved for the ATB (automatic train control and detection) signal and the other for return DC current. So with a double isolated track the resistance and inductance can be halved, meaning less losses [23]. The double legged system has a rail-inductor, two inductors with the centre connected to each other. This makes a path for the DC current to flow and connect the grounds together without providing a path for the 75 Hz. This can be seen in figure 2-8. In figure 2-9 one can see the single isolated section isolation. Here the grounding rail is not interrupted and the signal rail is interrupted.

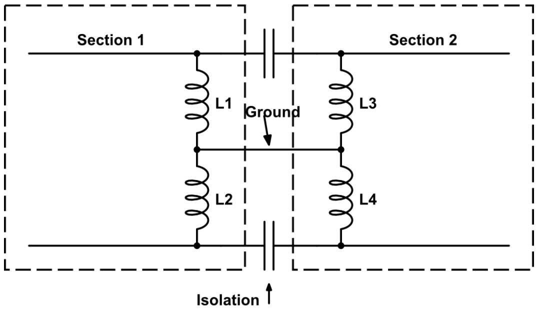

Figure 2-8: Two railway sections connected to each other with a rail inductor

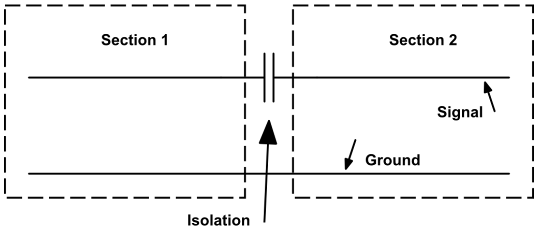

Figure 2-9: Two single isolated rail sections

Double isolated rail

The most used system nowadays is a double isolated system. It uses inductive filters to connect the DC-ground of both rails to the next set of rails without creating a path for the 75 Hz signal to flow.

The ballast resistance is dependent on the type of sleeper being used, type of ballast material, ground structure etc. [23]. The resistance is highly dependent on the moisture level of the ground. The resistance is proved to be in a range from $3 - 30\Omega$.

Because in a double isolated system the harmonic currents travel in both tracks, the potential between both rails due to the interference currents will be zero [13]. In the ideal double isolated situation no interference current will therefore flow through the relay, meaning that in that case no interference can exist. However when one of the tracks has suffered damage which has made an electrically isolation crack in the track or when the current flow in the tracks is not perfectly balanced a voltage between both rails can exist.

Single isolated system

The single isolated system is only used in places where there is no electrical traction used, on places that are not being used frequently and next to railroad switches. One advantage is that money can be saved on materials, because a rail-inductor is not needed.

2-4-6 Rail track

The return current and the ATB current have to flow through the rails. The rails have some impedance, consisting of a resistance, an inductance, a resistance to the other rail and earth and a capacitance to the other rail and earth. Also some variability in the parameters can occur:

- Multiple tracks next to each other which may also be used for the return current through a substation or ground short
- Single or double legged rail
- Distance to next section
- Amount of sections, thereby amount of section inductors

However one should think about the need to implement such complex system in the simulation system. In the end the idea of this research is to have an idea about the stability of the system. So it would be a better idea to model the rail as a simple RL circuit. The previous text was added when one wants to change the general model to a model that can be used to measure interference currents in the tracks. However in this thesis that will not be done because the focus is pointed towards the LC-filter.

The most used rail in the Netherlands is the UIC54 rail [24]. Typical parameters for the inductance and resistance of the rails can be taken as $R = 17.6m\Omega/km$ and $L = 0.7mH/km$ for double legged rail tracks [22] when using a simple series RL circuit.

2-5 The train

2-5-1 Input LC-filter

The input filters function is to filter the incoming harmonics and transients from the 1500 V line. It is positioned between the DC/DC converter and the pantograph. A typical LC filter consists of a capacitor and an inductor as can be seen in figure 2-10 [25][26]. However many different filter designs are possible. Dissipating bandpass filters are also used to dissipate the energy of a specific frequency band. Typical values for components in an LC-filter are in the range of a few mF and a few mH. The capacitance in this filter works also as energy storage for the traction motors. Because of this energy storage function the size of the capacitance can not be chosen too small. A large inductance is needed to help the current to flow constantly when having an air gap between the pantograph and the overhead line. When considering such filter design, one should also take note that this filter design has some resonance frequency. This frequency should not match another electric frequency in the system to keep the system stable. Also this resonant frequency should be kept above a certain frequency to meet product requirements. Generally the minimum frequency is set at 7 or 10 Hz. Therefore it is very important to take this component into consideration.

So the LC-filter has the following functions that determines the value of the components:

- Store energy in the inductance to help make an arc when the overhead line is suddenly separated from the pantograph
- Store energy in the capacitance to make the system stable
- Filter high frequencies distortions made inside and outside the train
- Have a resonance frequency above a certain minimum

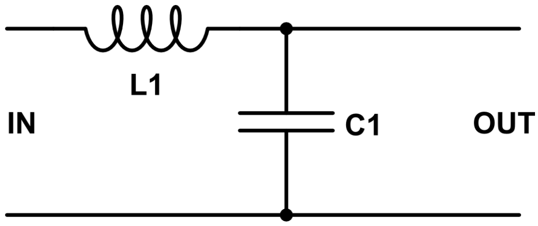

Figure 2-10: Typical second order LC-filter

2-5-2 Surge arrester

On top of the train is also a surge arrester placed. For this surge arrester the same applies as for the surge arrester in the infrastructure as described in section 2-4-3. So also this surge arrester will be excluded from the general train model.

2-5-3 DC/DC, DC/AC converter

In the train a DC/DC or DC/AC converter can be implemented. This converter is sometimes used in trains to make a stable voltage output for the other systems like traction inveters to work with. In the past the voltage requirements on the inverters where tighter then todays requirements. Because of that in older trains a DC link is mostly included. Some trains make AC out of the DC in order to be able to use a generic AC train for which a greater market exist and make it possible to feed the train with both AC and DC as can be seen in figure 2-11.

In this research a 1500 V train is used without a DC/DC converter.

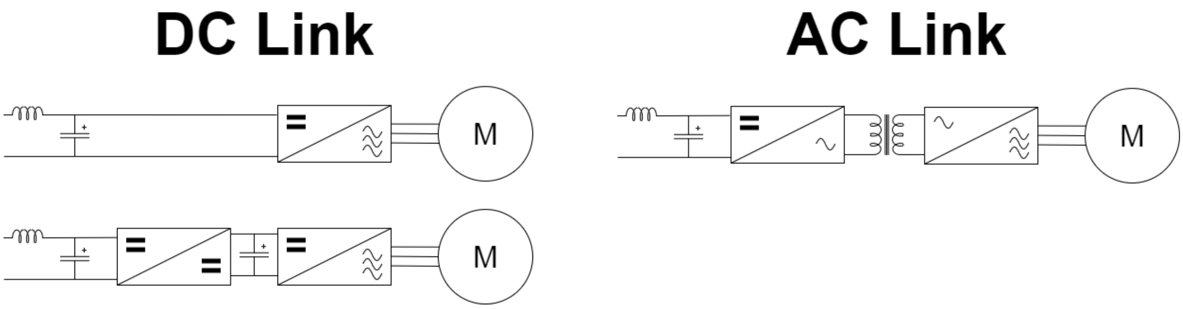

Figure 2-11: Different topologies for the converter in the train

2-5-4 Traction controller & converters

Today's trains are mostly powered by asynchronous traction motors. These traction motors need a three-phase inverter to be able to feed the traction motors with an AC voltage from a DC source. The inverter modifies its output frequency and the output voltage in order to control the torque the traction motors delivers. The traction motor drives the wheels and put in or take out electric energy in the train in the form of kinetic energy. It should be able to feed energy back into the grid.

Traction motor

The typical traction motor used in the research of Winterling about oscillations in rail vehicle traction drives, will also be used as example traction motor in this model [5]. The parameters used by that research can be found in table 2-1. Because the asynchronous traction motor is a squirrel cage rotor type no rotor winding connections are present. This improves reliability, reduces size and weight of the traction motor, operates in an enlarged constant power range, improves power quality and makes it less maintenance dependent than DC motors [15] [27].

Table 2-1: Traction motor parameters[5]

Stator resistance	R_s	0.127Ω
Rotor resistance referred to the stator	R_r	0.088Ω
Mutual inductance	L_h	$72.8mH$
Stator leakage inductance	$L_{s\phi}$	$1.81mH$
Rotor leakage inductance referred to the stator	$L_{r\phi}$	$2.62mH$
Pair of poles	p	2

Mechanics

The motor torque is transmissioned to the wheels via a gearbox and the wheels put the torque onto the railway. The train used in the thesis of Winterling had a gearbox ratio of 69/16 meaning that the motor is turning approximately 4.3 times faster as the wheels do, the wheels have a typical diameter of $0.92m$ and the weight of the train is $92t$ [5]. Wheel slip or drag coefficients of the wheels are not included in this system.

Controller & inverter

Next to this traction motor also a control system and inverter is needed. This system should control the torque and power flow to or from the traction motors by varying the output-voltage and/or frequency of the inverter.

When having a constant power control system a slightly drop in voltage can get the system in resonance because the current has to increase in order to get a constant power output. When current increases the voltages decreases further making the system unstable. The maximum current, power to the motors and torque at the wheels should be well controlled at all times to keep the system from exceeding its maximum values. Therefore a current limiting controller should be considered.

A typical asynchronous traction motor inverter is of a "two-level" type and has a circuit diagram as can be found in figure 2-12 [28]. The appropriate motor controller is important. The motors are by far the most powerful part of the whole system. Because of the constant power control it is also the most unstable factor of the system. It will be the most important factor in determining the stability.

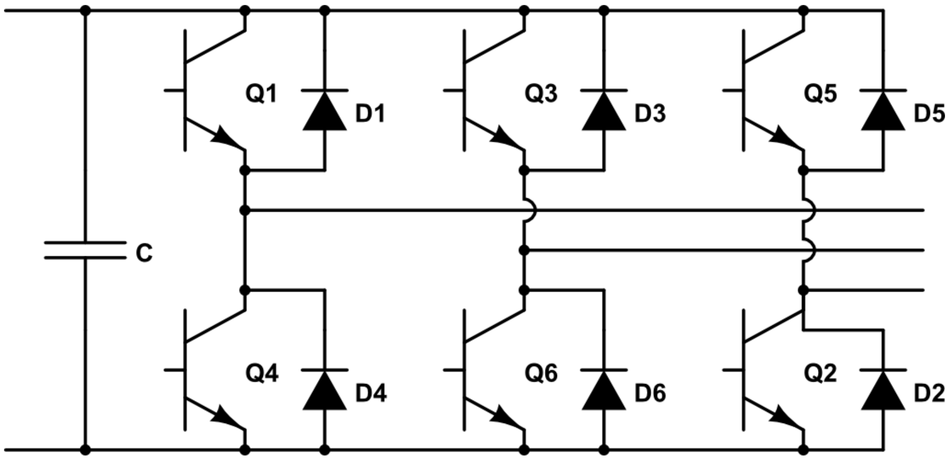

Figure 2-12: Typical VSI for an asynchronous traction motor

Current limiter

A current limiter is used to limit the current at very low and very high DC line voltages. The rules for this current limiter for a complete train can be found in article 19 of the Dutch railway law [4]. During motoring and a DC voltage higher than 1350V the maximum current a train is allowed to draw is 4000A. Under 1350V the maximum current is limited until it hits 0A at 1000V. These values are only for traction. Below 950V the undervoltage protection is activated. It will also disconnect the auxiliary loads. When in generation mode the voltage is not allowed to increase above 1950V and the generation should also be stopped at voltages lower than 1200V. This data can also be seen in figure 2-13 and figure 2-14 [4].

This system is useful because these systems are also implemented in the trains to meet regulations. It can help mitigate oscillations but can also help create new harmonics. Therefore it needs to be implemented in the system.

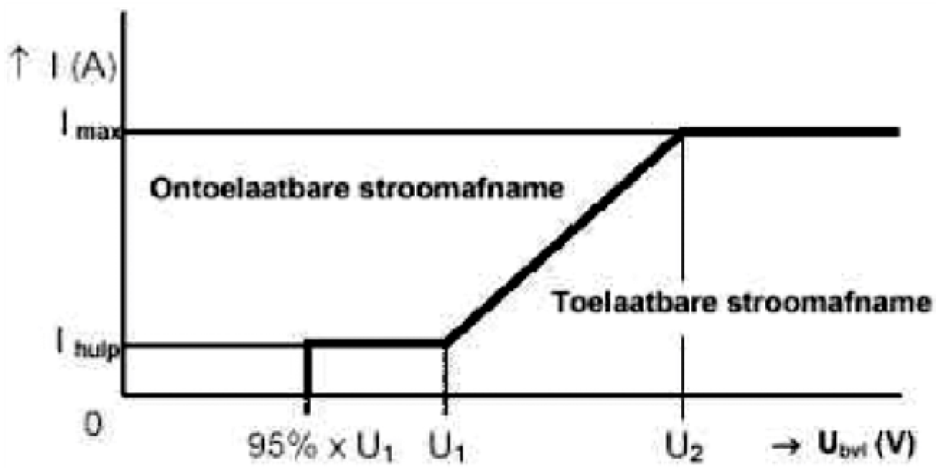

Figure 2-13: Maximum positive current against voltage [4]

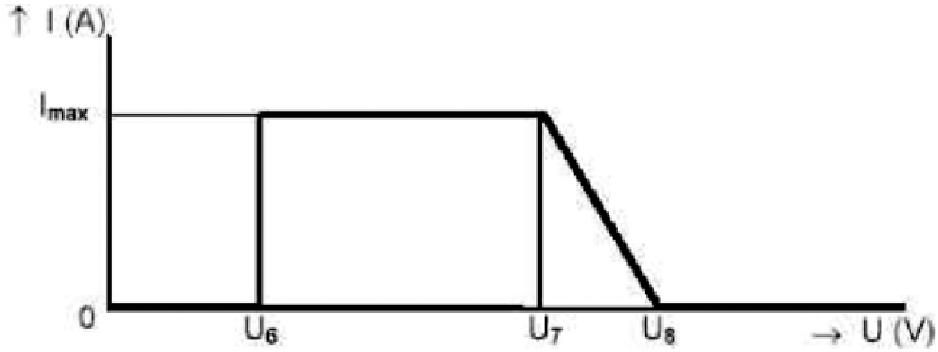

Figure 2-14: Maximum reverse current against voltage [4]

Power Limiter

Also a power limiter should me made in order to limit the power flow into the motors. The requested torque should be lowered in order to limit the amount of power. Otherwise the power would, with a constant torque, rise above the maximum power of the motors.

2-5-5 Auxiliary supply

The auxiliary supply is used to feed the on-board systems like lighting, computers, pumps etc. It is physically apart from the traction converter and can give multiple outputs both AC and DC. Multiple converters are used per train. Many trains have a separate auxiliary supply for the train systems and coaches. The amount of auxiliary supply, without heating, divided by the maximum traction power will give a value around $2-5\%$. In this research we will add 5% of the maximum traction power as auxiliary power for the general train.

In every train the auxiliary supply can be different. Not only the output voltage can be different but also the frequency differs. For a voltage controlled DC output a simple buck converter can be used in order to get the right voltage, but also a AC/AC transformer with rectifier can be used. In most trains a 3 or 1 phase AC output is necessary. Because of this variability in topology and outputs it will be an enormous task to get every topology or output in the system implementation. Note that an auxiliary converter is also a constant power load.

Undervoltage protection auxiliary

The auxiliary converter has an undervoltage protection. The requirements for this protection can also be found in article 19 of the Dutch railway laws [4]. One can find that the auxiliary converter should stop drawing current from the overhead lines when voltage drops below 950 Volts.

2-5-6 Brake chopper

In some trains also a brake chopper is implemented. This system consists of resistors which will be turned on, using a chopper, when voltages rises above a specified level. Because of this system, excess power which can not be fed back into the DC grid, can be dissipated in the resistors. This will lower wear on the frictional brakes by using more electrical braking power. Typical parameters for the resistance are around $3 - 10\Omega$. Because this system is voltage controlled it can be very helpful by stopping oscillations by dissipate the energy of the oscillation.

Chapter 3

Modeling and Implementation

In this chapter the parts which were discussed in the previous chapter, are going to be implemented in a simulation model. A simulation program will be chosen and every part of the system will be implemented in that system to form together the general train.

3-1 Choosing a simulator environment

The following requirements have been made for the simulation environment:

- The model should be a Graphical User Interface (GUI) model to make it easy to use
- Parameters of the different parts should be easy to modify
- Parts itself should be easy to modify
- Reasonable simulation time
- The program should be able to link the electrical system to the mechanical system
- Asynchronous motor and the motor controller should be available in the program
- Experience with the program is a pre

A few simulating environments have been considered. These are:

- Matlab Simulink
- Pspice
- Scilab
- Octave

- Freemat
- Modelica
- Mathcad

Simulink is a graphical programming environment for modeling, simulating systems in multiple domains [29]. The graphical environment makes it easy to keep overview and structure in the program. Also with the help of the Simscape and Simscape library unnecessary programming of standard blocks will be avoided. Many standard blocks like control systems and traction motors are already available and may only need a slight modification to get it to function in the desired way. Also the connection between the mechanical wheels and the electrical traction motors will be easy to make. Scilab, Octave, Freemat and Modelica are just alternatives for Matlab. Mathcad does not offer a Simulink alike for making the system in graphical way. Because Simulink met all of the above mentioned requirements and experience was present, Simulink has been chosen to be used in this project. The separate Simscape and Simscape power systems libraries will also be used in this model to implement the electrical and mechanical domain into Simulink.

3-2 Approach

In the next sections the process of making the subsystem blocks will be discussed.

To simplify the designing process, a modular system has been made. This means that every subsystem has been constructed apart from the rest, increasing their independence from the other subsystems and make problem solving easier. The most independent blocks have been constructed first. This because of the need to test the more complex blocks with the less complex and dependent blocks. All blocks have been tested for functionality before they are being used in the overall system.

First the systems in figure 2-1 have been divided into more manageable block sizes. The inputs and outputs with the configurable parameters of every block have been put in a table. Every part of this chapter got its own table with those details.

3-3 Simulation settings

When doing simulations one should think about step sizes, solvers, filters etc. An incorrect chosen step size, in particular a step size that is larger than half the time of the highest frequency, can result in aliasing. An approach could be to think about the highest frequency to measure multiplied with a value of at least 2. However in order to avoid aliasing there should be no frequency components beyond this point or an extreme steep filter set at the maximum frequency should be used. One does not know what the maximum frequency of the system is and extreme steep filters are not practical so one should make a good combination between a low enough step size, to be able to simulate the system within a certain amount of error, and practical filters that can filter higher order frequencies from the results showing components. Lowering the step size will increase memory use and simulation time.

There is a relative large inductance and capacitance in the circuit, both in the train as well as in the overhead line, very high frequencies should not be able to appear in the system. Meaning that there should be some limit to the maximum frequency that is necessary to sample.

A typical LC-filter with overhead line components have been modelled in figure 3-1. L3 represents the line inductance. L1, C1 and R2 represent the LC-filter. R3 represents a load of around 1 MW. In figure 3-2, one can see that the transfer from source to load is very low at frequencies above $100Hz$, meaning that the LC-filter is preventing high frequency currents to flow outside the train. Note that these high frequency currents can still flow inside the train. Also note that at higher frequencies the inductance of the LC-filter can start to behave more like a capacitor than an inductor, because of the capacitance effect between the windings of the inductance. Meaning that at high frequencies the inductance may not be able to filter them anymore.

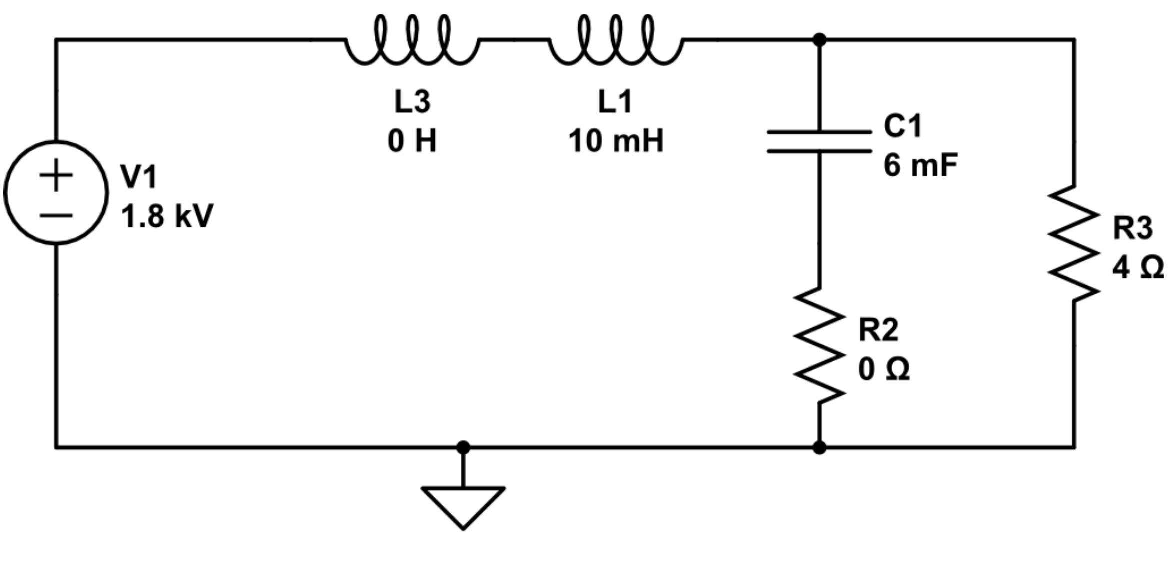

Figure 3-1: Testing circuit for the frequency characteristic of the LC filter and overhead line

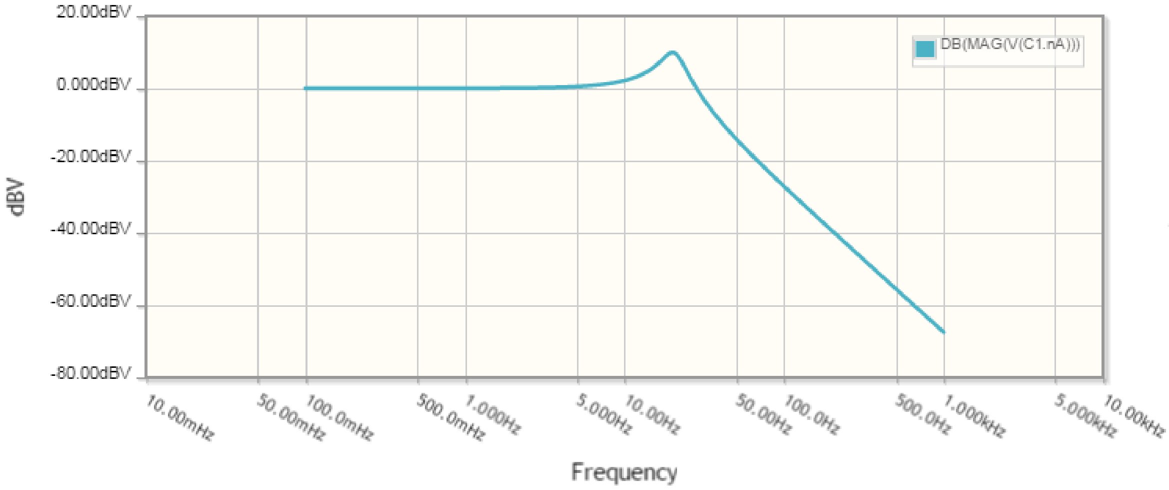

Figure 3-2: Frequency vs voltage amplitude, at load-resistance, graph of the testing circuit, measured over resistance R3

When using the automatic option of Simulink, a variable step size with a maximum step size of $1 \cdot 10^{-6} seconds$ will be selected. Using a variable step size has several advantages over fixed step size. It can take larger time steps while still giving the same results, thereby using less system resources to do a simulation. With this step size the memory use is limited when using sampling at a lower frequency of plotted, and thus stored in memory, signals. In the simulation two kinds of output exist. One is the "scope", this block plots the signals on a time base in a graph. To keep memory use limited one should limit the amount of stored values for such plot. A block called "Zero-Order Hold", which is an asynchronous sampling block, has been used to lower the sample frequency to a value of $1kHz$. The other output, the "Spectrum Analyzer", plots the Fourier transform of the signal on a dBm versus frequency graph. Here it is very important to have good filtering in order to prevent aliasing. In appendix C a separate chapter has been made to discuss about aliasing in the spectrum analyser. Knowing the phenomena of aliasing is basic understanding in the world of electrical engineering, however can easily be forgotten. Therefore it is added as appendix in this thesis.

3-3-1 Solver

Simulink can use multiple solvers in order to have a better fit with the system. Solvers can be continuous or discrete. Simulink also has an automatic option where it selects the most appropriate solver for the system. The ideal solver should do the following [30]:

- "Solving the model successfully"[30]
- "Provide a solution within the tolerance limits you specify"[30]
- "Solve the model in a reasonable duration"[30]

When using the Simscape Power Systems extension, the automatic solver selector should choose the ode23tb automatically because of nonlinear models (like diodes) in the system

[31]. However ode23t is automatically selected by Simulink. The discrete solver can not be used because the model contains continuous states. Ode23tb will be used in this thesis because that is the solver which is advised for Simscape Power Systems.

3-4 Modelling the rail infrastructure

Like chapter 2, this chapter will be split in two sections. First the infrastructure blocks will be discussed and after that the train will be discussed.

3-4-1 Substation

The substation block may consist of a 6 pulse, 12 pulse or 24 pulse rectifier. Rectification in the networks is done by using diodes not thyristors. The output of this subsystem block consists of a positive and negative DC connection. There is no input since the grid connection should also be in this block. In the options of this block a choice should be made for the right rectifier topology and the amount of imbalance of the three phase grid connection.

Table 3-1: Inputs, outputs of the substation block

Output	
+	Output positive voltage
-	Output neutral voltage
Parameters	
Amount of pulses	Choose between 6, 12 or 24 pulse rectifier
imbalance	Imbalance of phase B (%)

When doing research into the harmonics generated by the rectifier, first a simple balanced grid with a single transformer with a wye (Y) and a delta (D) secondary winding and 12 diodes have been used as can be seen in figure 3-3. Because this is a 12 pulse converter one would expect harmonics at multiples of 600 Hz (=50Hz*12diodes). When looking at figure 3-4 one can see that the main distortion frequency is indeed 600 Hz.

The output of the this subsystem should give around 1950V DC with some harmonics at the right frequency depending on the chosen rectifier. This is done by simulating diodes and transformers in Simulink. The AC inputs in this model is $V_{Line-to-Neutral} = 13.75kV$. A three-limb core transformer with 2 secondary windings has been used. One of the output is in Delta1 configuration, the other is in wye configuration. To make the output voltage uniform when having a load connected one needs the delta transformer to have a three times higher ohmic resistance as the wye transformer. This is because the way the three phase transformer windings are connected to each other. With the configuration in figure 3-3 this will give a peak output voltage of $1944V$ which is too high, that is because a step-changer is being used. This stepchanger is configured to give an output of approximate 1800 V under light loads. Therefore a correction factor of $\frac{1800}{1944}$ has been added to the output voltage setting of the model block. Note that there is no capacitor connected to the output of the rectifier this because the $100\mu F$ capacitance has too little energy storage capacity to influence the system. In simulations it has been proven that the capacitance does not influence the results of the system.

Also a parameter for the amount of imbalance of the grid can be given. This will simulate the imbalance and produces harmonics accordingly. The effect of giving the B phase a reduced amplitude of 90% can be seen in figure 3-5 in comparison to figure 3-4 where the phases where in balance.

In figure 3-6 and figure 3-7 one can see the spectrum analysis for the voltage across the resistance in figure 3-3. The substation is of a 12 pulse type and therefore the main harmonic in the balanced situation is at 600 Hz as can also be seen in the figures. In the imbalanced situation the harmonic due to the imbalance is at 100 Hz and a lot side harmonics (+-100Hz) are present around the basic harmonics giving a very distorted signal. So high voltage imbalance conditions should be prevented to prevent large harmonic current flow.

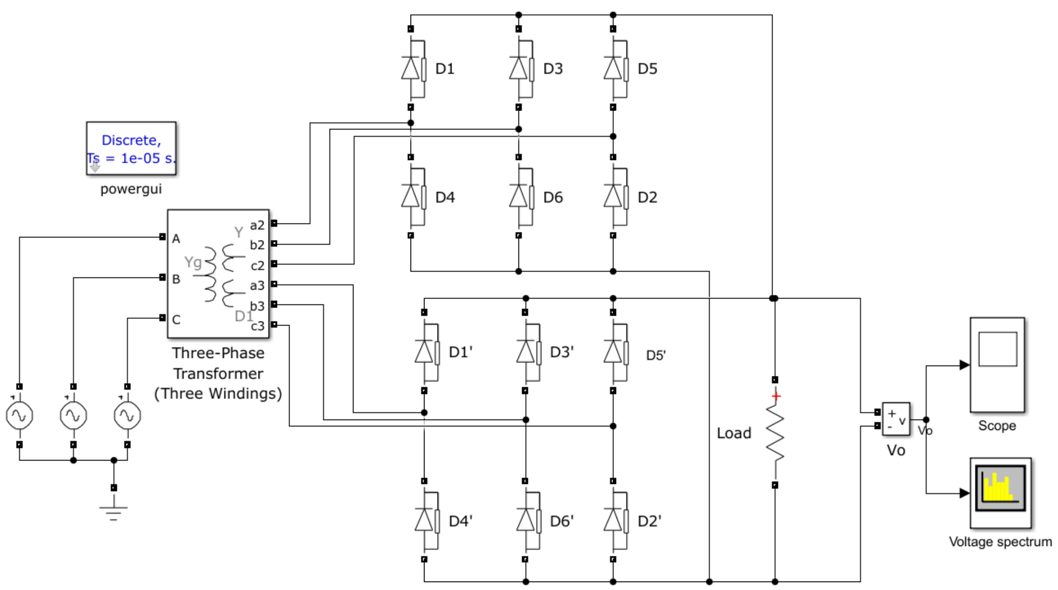

Figure 3-3: Rectifier model, 12 pulse rectifier

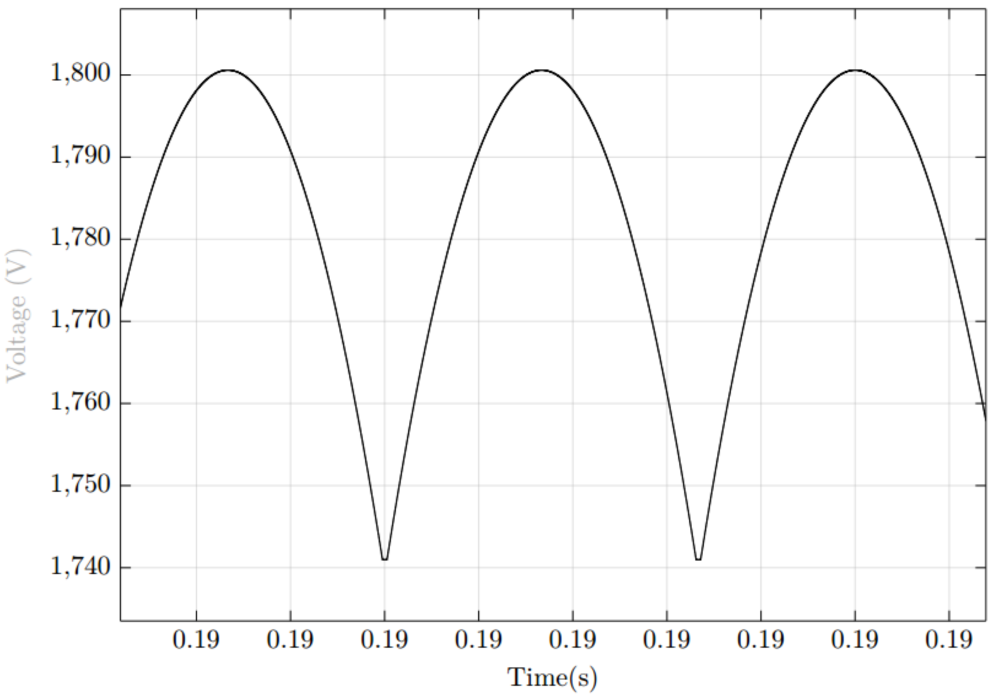

Figure 3-4: V_{out} for balanced grid, 12 pulse

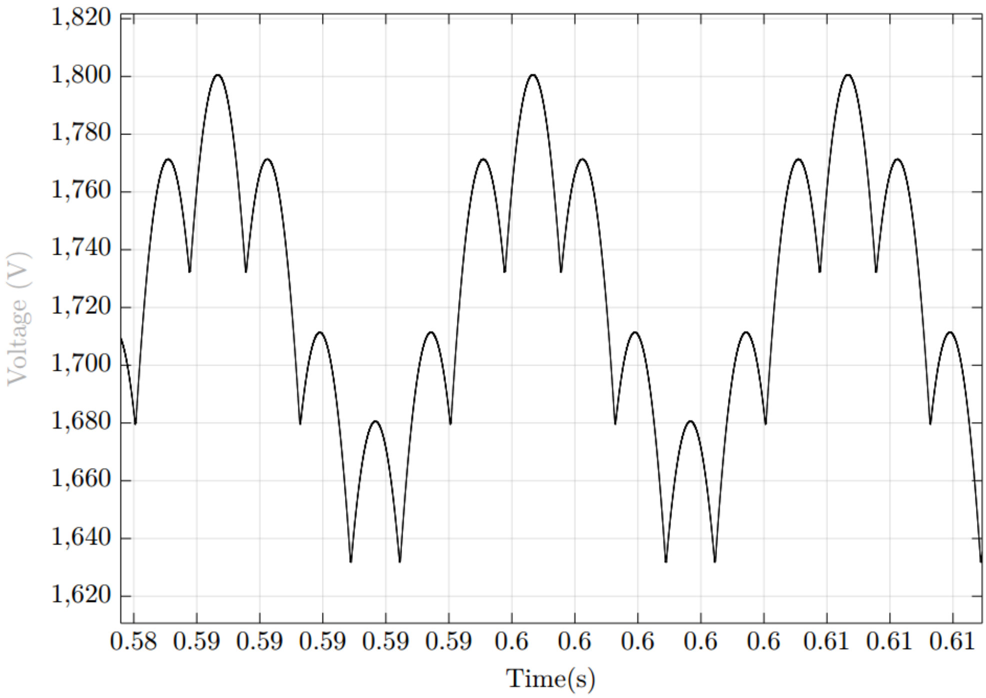

Figure 3-5: V_{out} for imbalanced grid (voltage phase B 90% of 13.750 kV), 12 pulse

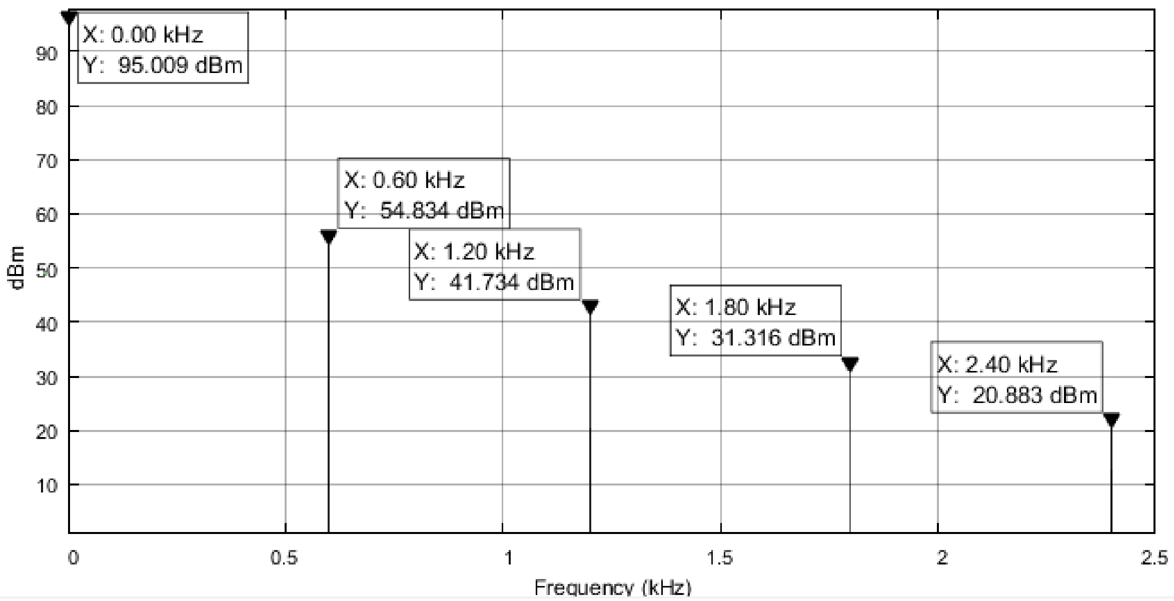

Figure 3-6: V_{out} spectrum analyser for balanced grid, 12 pulse, RBW: 1Hz, Rectangular 10%

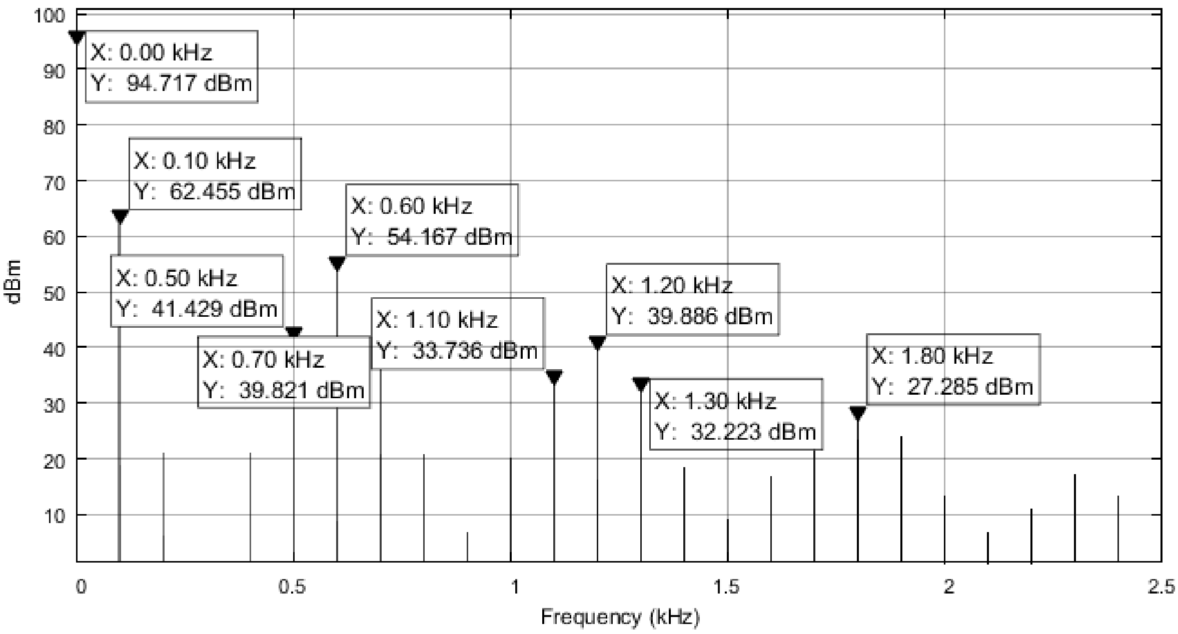

Figure 3-7: V_{out} spectrum analyser for imbalanced grid (voltage phase B 90%), 12 pulse, RBW: 1Hz, Rectangular 10%

The importance of this block is to implement the switching harmonics into the system. However when using a 12 or 24 pulse rectifier and LC-filter, most of the harmonics can not reach into the train. In situations were it is not that important to come that close to reality the substation could be changed for a constant voltage DC source with a series diode.

3-4-2 Variable length overhead line and Rail impedance

Table 3-2: inputs, outputs of the overhead line block

inputs	
+	Inputs positive voltage from substation
-	Inputs ground from substation
Output	
+out	Output positive voltage to internal bus
-in	Output ground to internal bus
Parameters	
Line inductance	Inductance of the line (H/km)
Line resistance	Resistance of the line (Ω/km)
Rail inductance	Inductance of the rail (H/km)
Rail resistance	Resistance of the rail (Ω/km)
Distance	Distance from train to nearest substation (km)

The overhead line consists of an inductance and resistance. The inductance and the resistance are dependent on the distance from train to substation. Parameters like distance, resistance and inductance of the overhead line in Ω/km and H/km should be given to this block for correct modelling of the overhead line. The block and model used for this study can be seen in figure 3-8 and figure 3-9. As can be seen in the model a resistance is added across the inductance. This is to help the simulator cope with the inductance with initial current setting. A very high value is used in order to not influence the simulation results.

Also the rail parameters are implemented in this block. Here the same rules apply as for the overhead line. A total resistance and inductance of a section is calculated based on the same distance as the overhead line is.

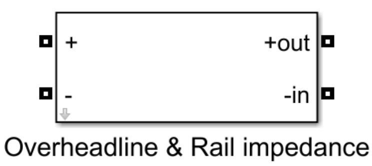

Figure 3-8: Overhead line block part of the system implementation, showing inputs and outputs

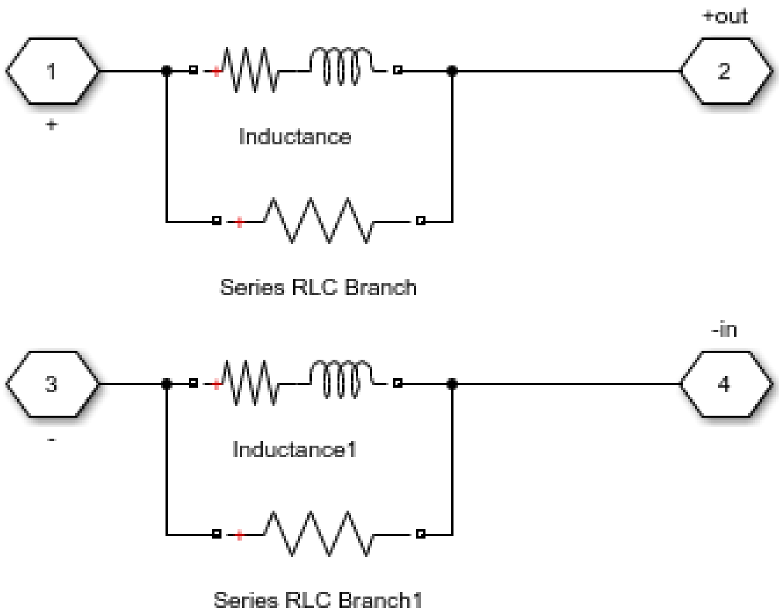

Figure 3-9: Overhead line filter model

3-5 Modelling the train

3-5-1 Input LC-filter

The LC-filter (figure 3-10) consists internally of an inductance and capacitance as can be seen in figure 3-11. The block in and outputs and parameters can be found in table 3-3.

Table 3-3: inputs, outputs of the LC-filter block

inputs	
+	Inputs positive voltage from substation
-	Inputs neutral voltage from substation
Output	
+out	Output positive voltage to internal bus
-out	Output neutral voltage to internal bus
Parameters	
Capacitance	Capacitance of the LC filter (F)
Inductance	Inductance of the LC filter (H)
Initial current	Initial current of the inductance (A)
Initial voltage	Initial voltage across the capacitance (V)

Parameters for the LC filter are not dependent on the distance. They are just a constant capacitance in F and a constant inductance in H. Also the initial current and voltage of the filter elements should be given.

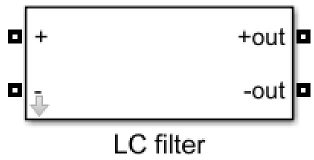

Figure 3-10: LC-filter block

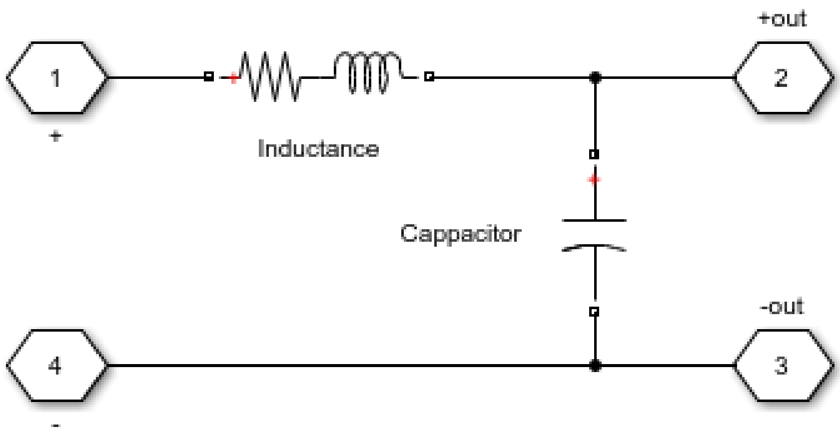

Figure 3-11: LC filter model

3-5-2 DC/DC, DC/AC converter

As already explained in chapter 2-5-3 the DC/DC converter will not be implemented in the general train model. One could ask the question why to discuss this part when it is not going to implemented in the model. However it is a good reminder for future investigation, that there may be a DC/DC or DC/AC converter at that particular place. Also this block will be used for the train in chapter validation. The block can be found in figure 3-12

Figure 3-12: The DC/DC or DC/AC converter block part of the system implementation, showing inputs and outputs

Table 3-4: Inputs and outputs of the DC/DC converter

DC/DC converter	**Input**	
	+	Input positive voltage from LC-filter
	-	Input ground voltage from LC-filter
	Output	
	+out	Output positive voltage to internal bus
	-out	Output ground to internal bus

3-5-3 The complete traction

The traction motor that will be used is the three-phase asynchronous motor. In Simulink this sort of traction motor is already available in the Simscape library. When using this block the relevant parameters of a traction motor used in the trains should be known. Many available motor parameters are not given in the same equivalent scheme as Simscape requires them to be, giving rise to translational problems between different equivalent models. It has been chosen to use the parameters that can be found in reference [5]. These parameters are in the same equivalent model as Simscape request them. The downside of this motor however is that it had been used in a train with a DC bus voltage of 2300 V[5] while the DC railway model has no boost converter to increase the voltage.

Mechanical system of the train

This block simulates the train mass, friction, gearbox and also calculates the torque and power at the wheels, wheel speed and train speed. It should be connected through the mechanical rotational port to the corresponding port on the traction motor. The block can be seen in figure 3-13 and the system can be seen in figure 3-14.

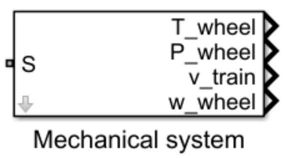

Figure 3-13: Mechanics block part of the system implementation, showing inputs and outputs

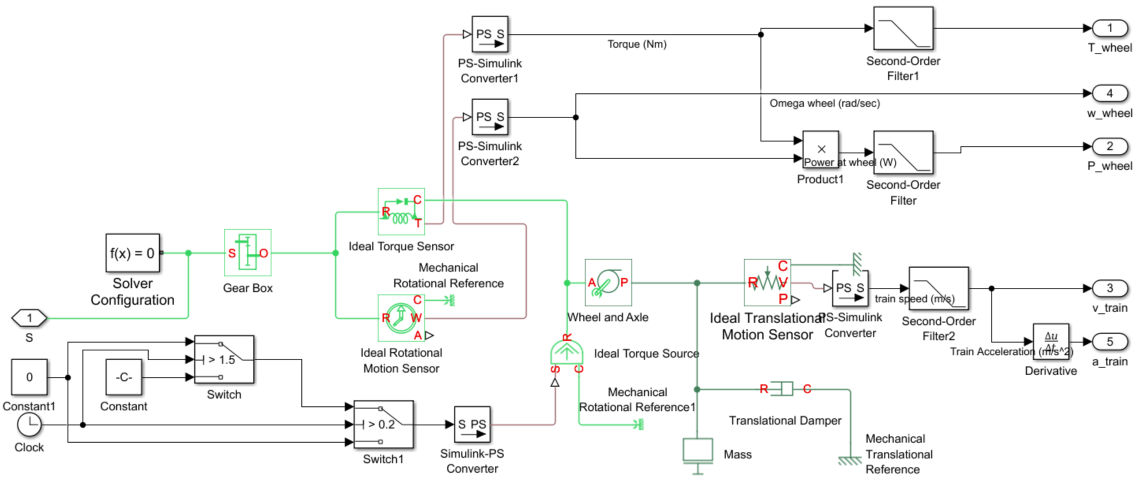

Figure 3-14: Mechanics model

The mass of the train, gearbox ratio, wheel radius and friction constant are parameters for the block. The output measurements like power and torque at the wheels can be very helpful when solving problems in the combined system.

Table 3-5: Inputs, outputs and parameters of the mechanical system

inputs	
S	Mechanical rotational port
Output	
T_wheel	Torque at the wheels (Nm)
w_wheel	Rotational speed of the wheels (rad/sec)
v_train	Speed of the train (m/s)
P_wheel	Power at the wheels (W)
Parameters	
Radius	Wheel radius (m)
Gearbox	Gearbox ratio (motor/wheel)
Mass	Mass of the train (kg)
Friction	Friction coefficient (N/(m/s))

The system has been made in the mechanical system of Simulink and can be seen in appendix figure 3-14. The S incoming port is the connection to the traction motor. Directly behind this incoming connection is the gearbox. After measuring the torque and the rotational speed at the wheels, another block is present to simulate the wheel diameter. At the axle of the wheel an ideal torque source is connected. This torque source will be used in some simulations to quickly ramp up the train speed. The air and rolling friction and the mass of the train are simulated at wheel to rail level. So the friction is train speed dependent. Also the train speed is measured and exported. All inputs, outputs and parameters can be seen in table 3-5.

Traction motor

This traction motor needs a 3 phase AC input, a mechanical in/output for external force and a measurement output including rotational speed in rad/sec and torque.

The importance of this block is to simulate the traction motors with the right power flow in order to be able to simulate the system in most of the system states. One should think about simulating at different speeds and requested torque.

Table 3-6: inputs, outputs of the asynchronous motor

inputs	
A, B, C	Three phase AC inputs. Connected to inverter or AC Source
S	Mechanical rotational port
Output	
m	A vector of measured signals, including but not limited to rotor speed and torque
Parameters	
Rotor type	squirrel cage is used here
Power	Nominal power (VA)
Voltage	line to line voltage (V)
Frequency	Nominal frequency (Hz)
Rs	Stator resistance (Ohm)
Lls	Stator inductance (H)
Rr'	Rotor resistance (Ohm)
Llr'	Rotor inductance (H)
Lm	Mutual inductance (H)
slip	Initial slip

Inverter

Because a variable frequency voltage source should be made out of the incoming DC power line, one should use an inverter and a PWM signal to construct an equivalent of a three phase AC voltage. The standard inverter block from the Simscape library has been used to make the three phase voltage.

Traction motor controller

A system has been made to be able to test the control system. The previous made mechanical block, the energy meter block and the inverter block has been used to make a relative simple model to test the control system in. An asynchronous motor has been used with typical train parameters as explained above.

First a system which uses a simple fixed frequency three phase ideal voltage source has been connected to the traction motor. This scheme can be seen in figure 3-15. The used frequency is 10 Hz and $V_{RMS,ph-ph} = 400V$. No external torque is applied. The scope is displayed in figure 3-17. The upper figure is the motor speed, in the middle the torque the motor applies can be seen and in the lower figure one can see the voltage and current waveforms. It speeds up to a fixed rotor speed just like expected and at that speed no torque is delivered. Note that due to reactive currents in the motor, still a small current flows while torque is zero. The power at torque is zero is almost zero.

So it has been proven that a fixed frequency voltage source can get the motor to turn. However to work in the most efficient or highest torque output region one would like to couple the rotational speed to the frequency of the source. First a system using inverters, with also a fixed frequency, instead of an ideal voltage source has been made. This system can be seen in figure 3-16. The scope for this system can be seen in figure 3-18. When comparing this figure to figure 3-17 it can be seen that the differences can be found in ripples in the signals. The output voltage ripple consist out of the 5th and 7th harmonic of the 10 Hz signal frequency. In the torque signal a 6th harmonic of 10 Hz is present. In the current on the input side of the inverter a 6th harmonic of 10 Hz is present. All are in accordance with the expectations of an inverter fed traction motor. Both configurations have around the same final speed.

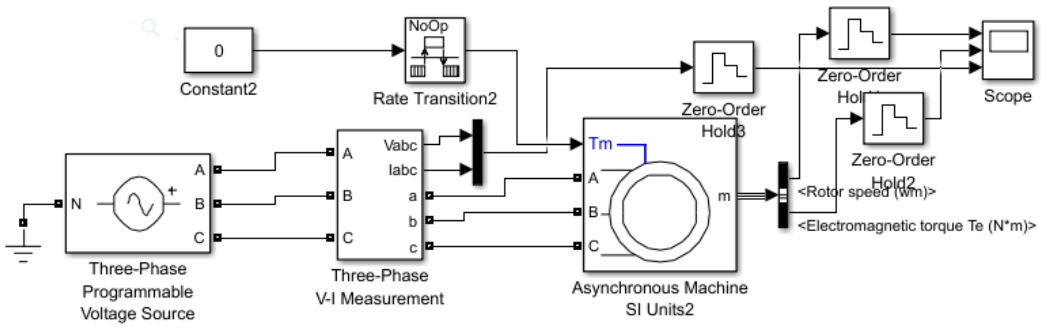

Figure 3-15: Testing of the asynchronous motor with a simple three phase voltage source

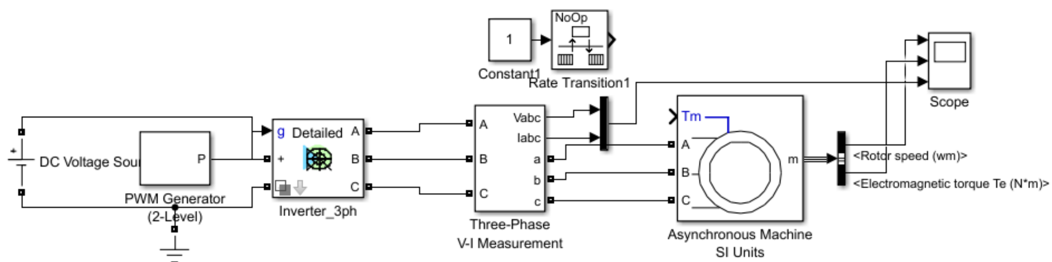

Figure 3-16: Testing of the asynchronous motor with an inverter (PWM, 10Hz signal onto 1000Hz carrier, modulation index = 0.8) voltage source

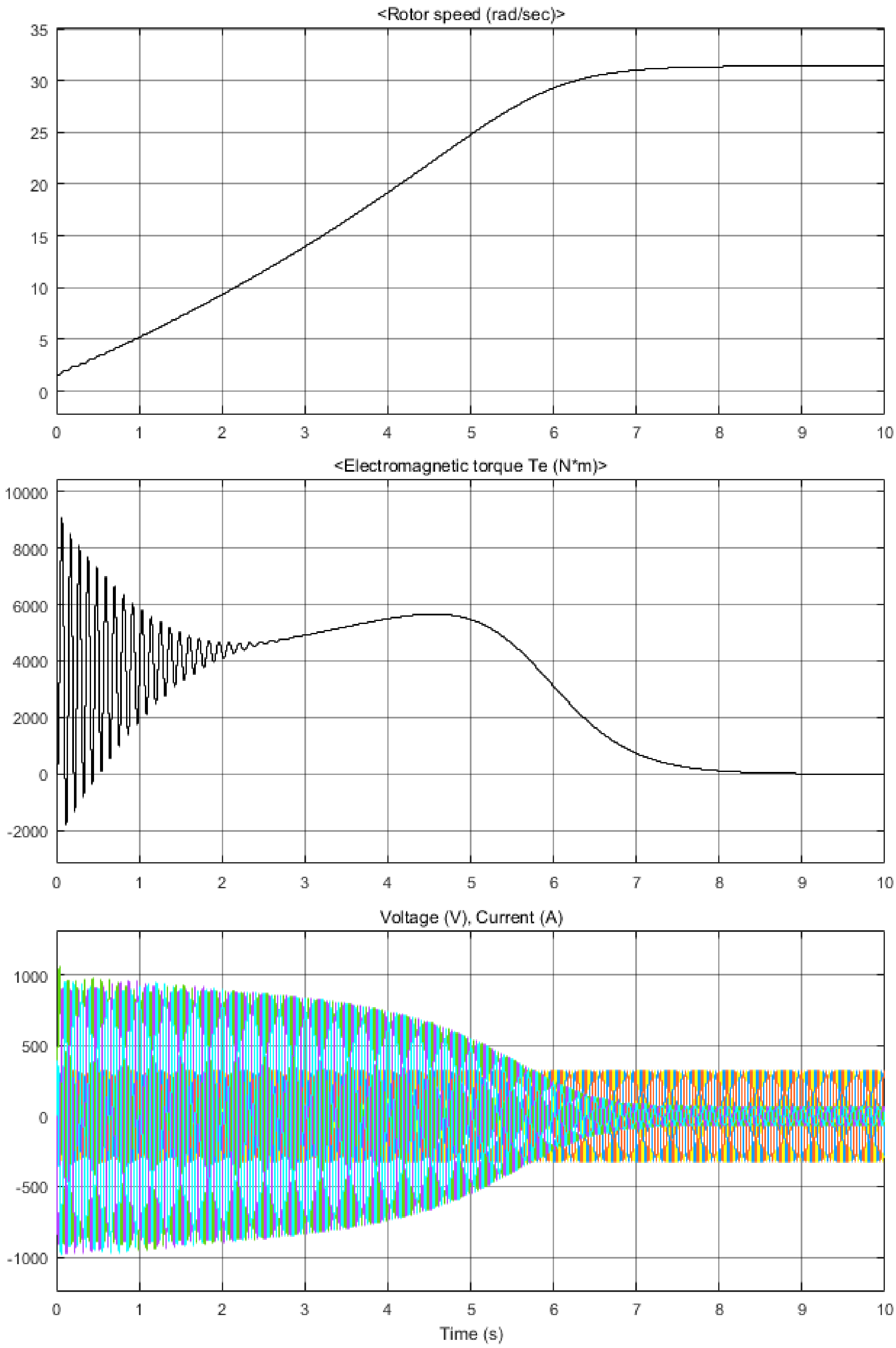

Figure 3-17: Simulations of an accelerating motor with a simple fixed frequency source 400V, 10 Hz

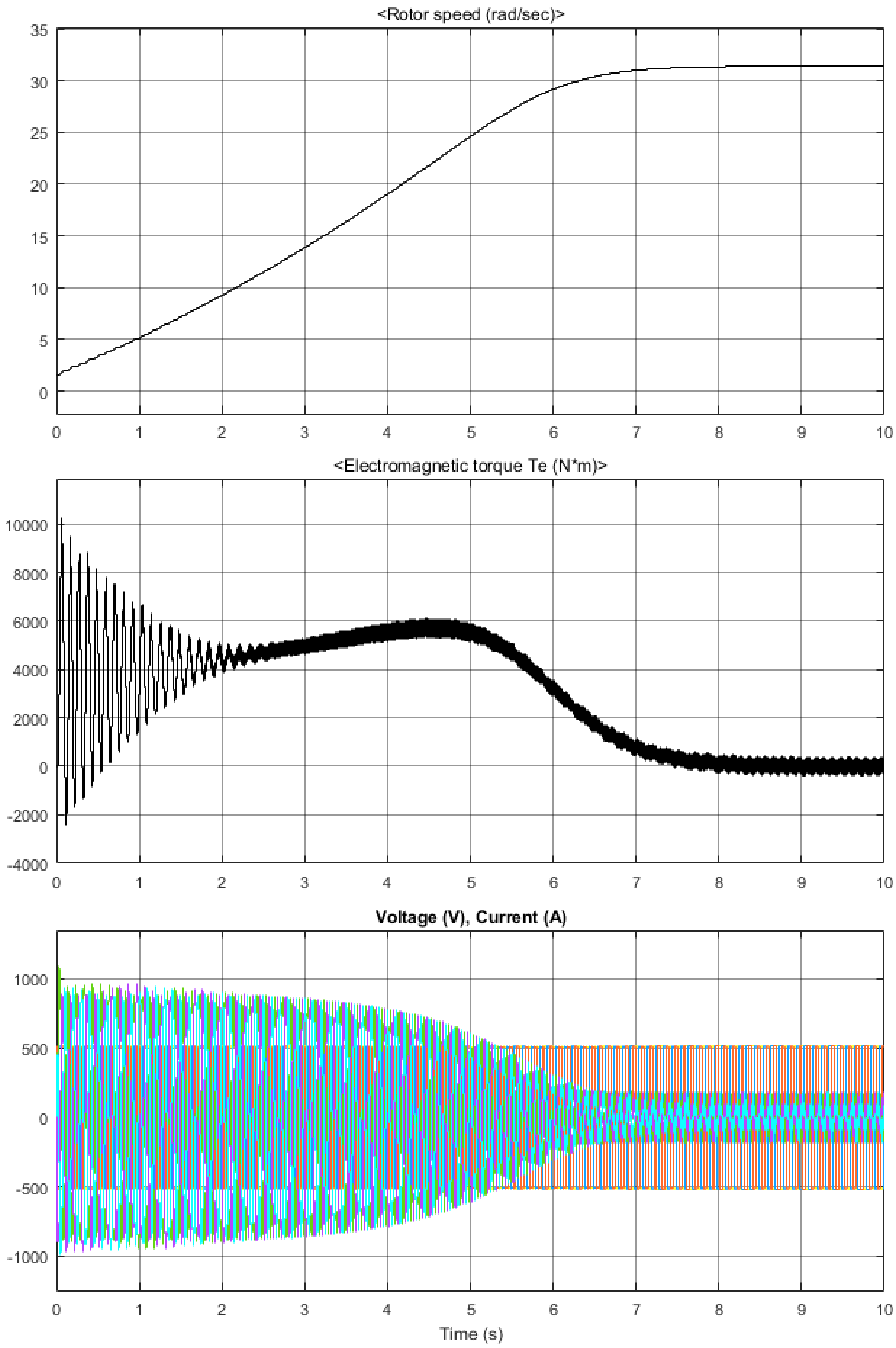

Figure 3-18: Simulations of an accelerating motor with an inverter source with fixed frequency 400V, 10 Hz

At the point where the inverter voltage source structure was working, a variable frequency source was the next logical step. It was relative difficult to make a variable frequency voltage source in Simulink (making a variable sinus block is not so straight forward as might thought), therefore the idea became to change to a system with an inverter and a control system with Direct Torque Control (DTC). Initially this system was working however the control seemed problematic. It gave a starting torque, but after a few milliseconds it seized operation for some unknown reason. The results of this unstable system with DTC control can be seen in figure 3-19. Here the torque at the wheels, the power at the wheels and the train speed are shown. It is easy to see that the acceleration and the power at the wheels both are very low. In contrast to the power that goes into the system, which is $\approx 68kW$ (not shown).

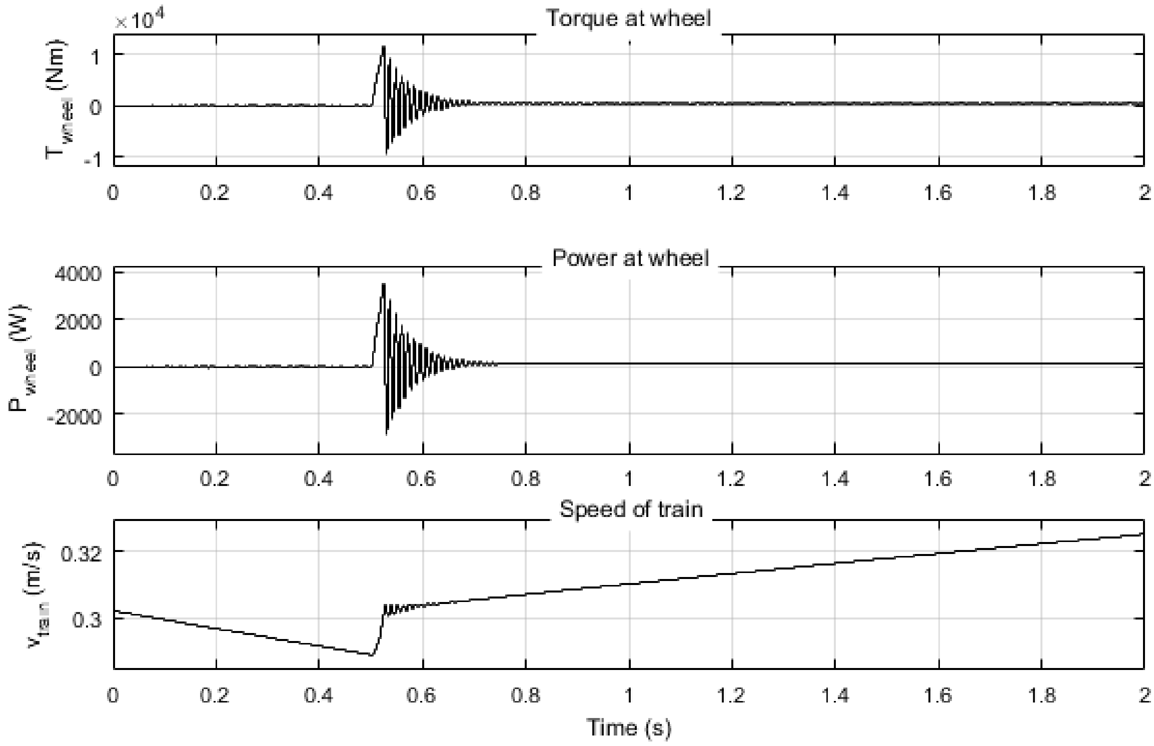

Figure 3-19: Unstable machine controller using DTC

When it became clear that the DTC controller was not going to work, a Field Oriented Controller (F.O.C.) was chosen. This controller resulted in better stability and better controllability of the motor torque. A F.O.C. needs the rotational speed of the motor in order to control the motor[32]. The system implementation of the field-oriented controller can be found in figure 3-20. One can see that next to the field-oriented controller block, here named "F.O.C.", a torque controller block is present. Using of this block is general practice when using a F.O.C. controller. It enhances the incoming requested torque signal to prevent overshoots and transients. It incorporates a PI controller. The inputs of the torque controller block is the speed of the motor in rad/s and the requested torque. The requested torque is externally made. This will be discussed later. The F.O.C. block inputs the rotational speed of the motor, the inverter phase currents, the requested flux and the requested torque. It outputs the gate signals for the inverter, Magc and theta. MagC is a Boolean signal that represents the state of the motor. When the traction motor is magnetised enough to start this signal will be high. The Magc and Theta signals are not used. Both the torque controller (originally named "Speed controller (AC)") and the Field-oriented controller are standard Simscape system blocks.

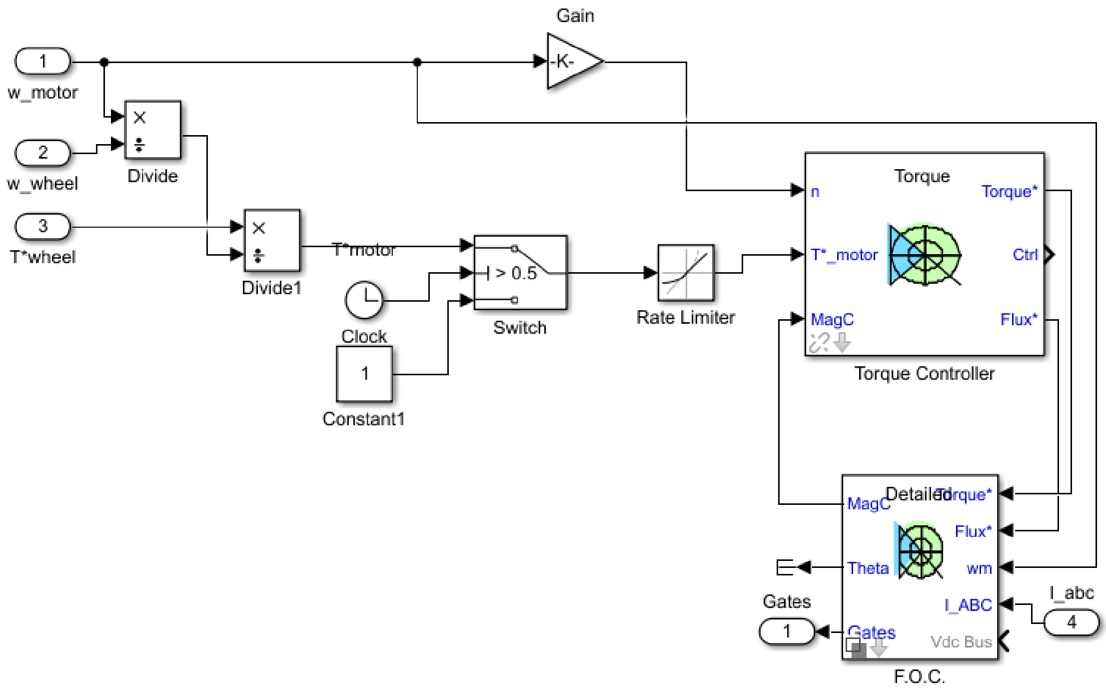

Figure 3-20: Traction motor controller block

However, instability can also occur in the field-oriented controller. For example when the resonance frequency of the LC-filter and overhead line lies in the bandwidth of the motor controller. Resonance will happen when the inductance is too large or the capacitance of the filter is too small for the power usage of the traction unit. This event will be discussed later in this thesis. In order to make the system as close to reality as possible (which include limitation systems) one should make changes to the requested torque and make it dependent on the current, power and bus voltage. At least three systems have been used for this purpose, the current limiter, the power limiter and the torque limiter. These systems have been combined into one system named "Torque and power limiter".

Flux control

When doing a complete cycle of a train with a fixed amount of flux, some problems arise with efficiency and with the maximum speed for full power. Some research has been done to the relation between flux and speed, maximum power and efficiency. Three different amount of flux values will be tested, namely 5.0 Wb, 3.0 Wb and 2.0 Wb. In figure 3-21 the system used to test the response to a fixed flux can be seen. In figure 3-23 and 3-24 the simulation results can be seen. In figure 3-22 the Toque, power, speed graph can be seen from an idealised system can be seen. The parameters used for this test can be seen in table 3-7. This is a typical result for all test. Note that at $t = 15$ the motor switches from motoring mode to generating mode.

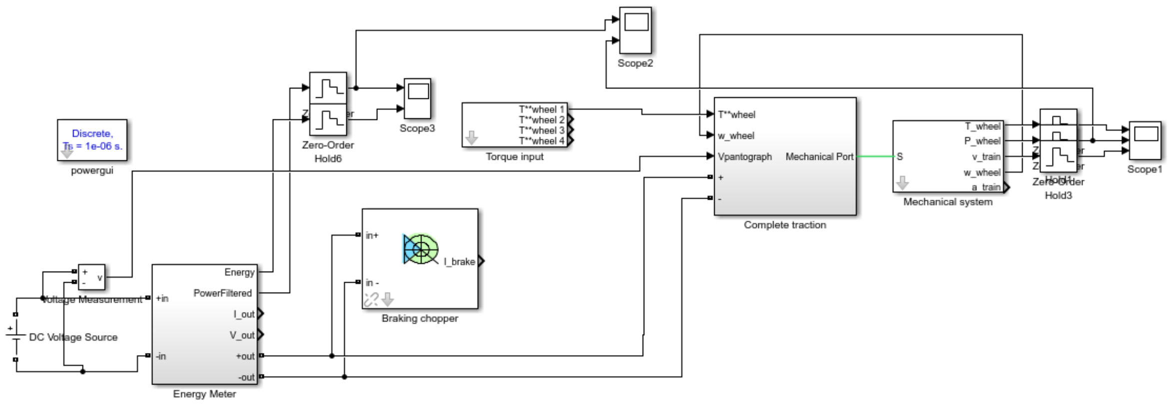

Figure 3-21: Testing scheme for different amount of flux

todo:change pic

Table 3-7: Parameters for flux test model 1

Used parameters for Flux test 1	
Source	Simple DC voltage source, no diode, 1500V
motors	4 motors connected to 1 control unit
Auxiliary supply	Not used
LC-filter	Not used
Overhead line	Not used
Rail track	Not used
Braking chopper	Not used
Torque	At t=0.3s: $T_{requested} = 99kNm$, At t=15s: $T_{requested} = -34.5kNm$

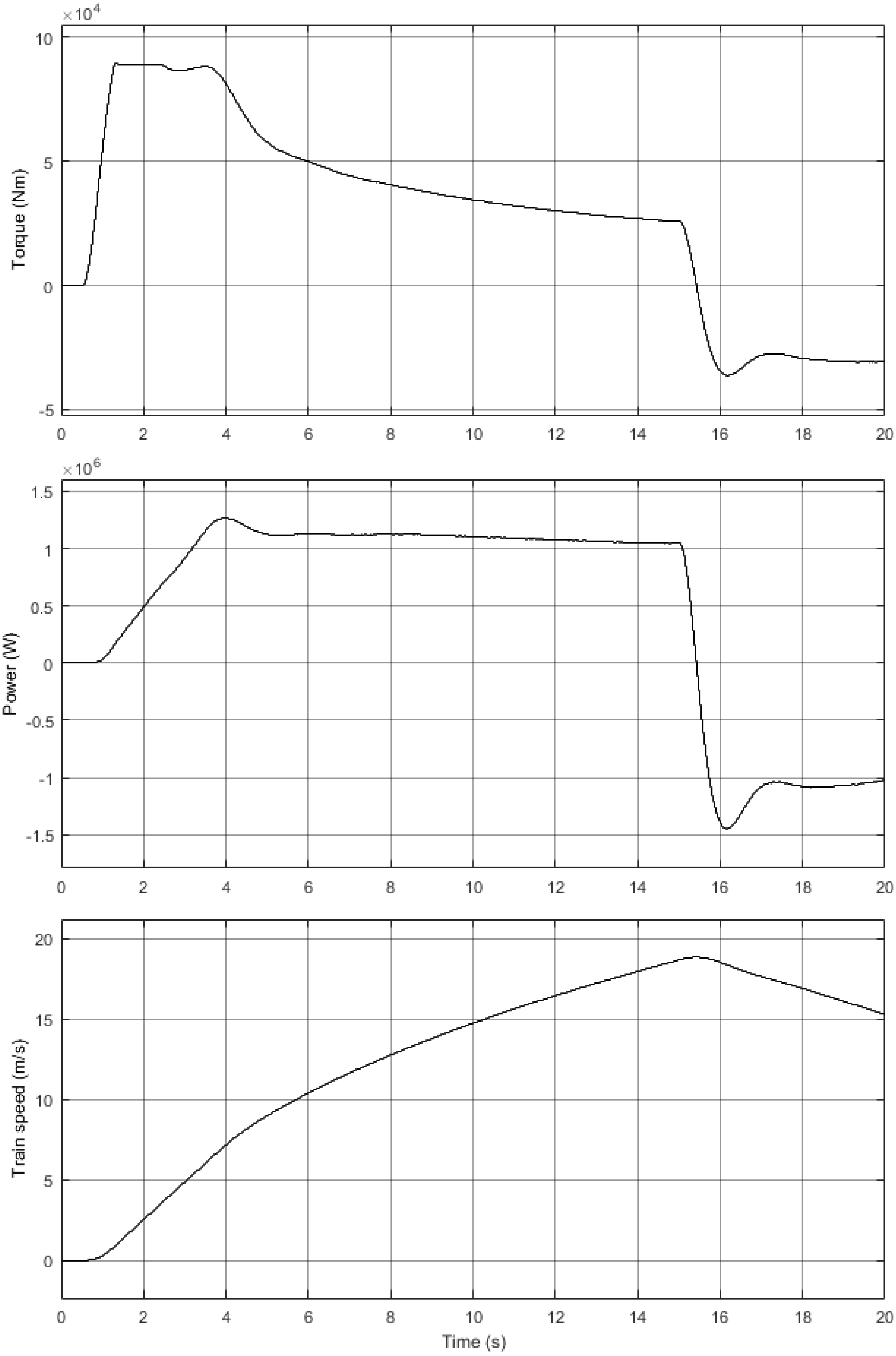

Figure 3-22: Torque, Power and train speed graph of a typical simulation

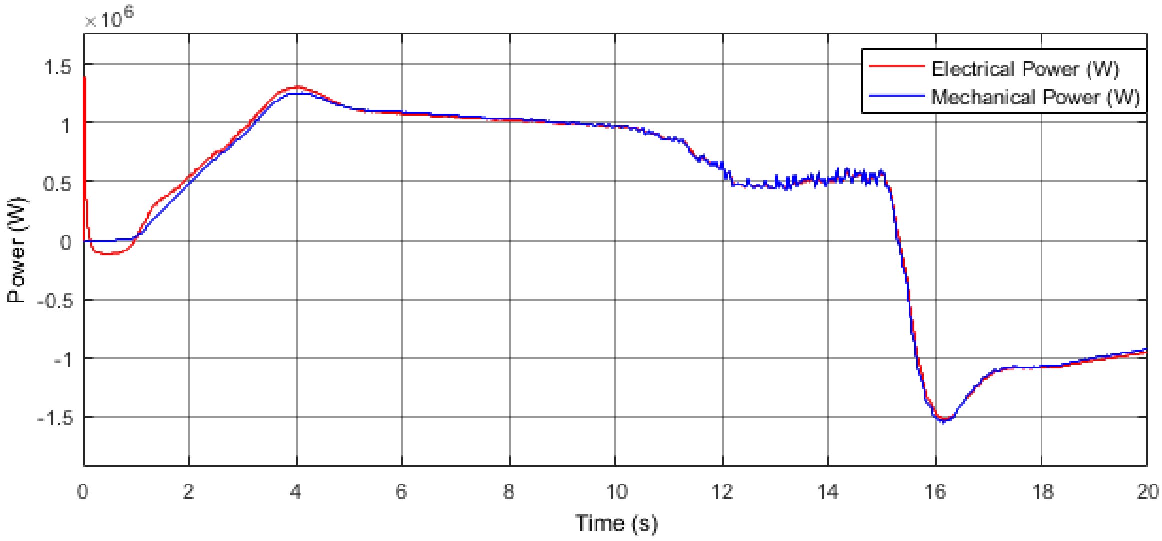

Figure 3-23: Mechanical power (blue), electrical power (red) flow into or out of the motor, 1500V and Flux = 5.0 Wb

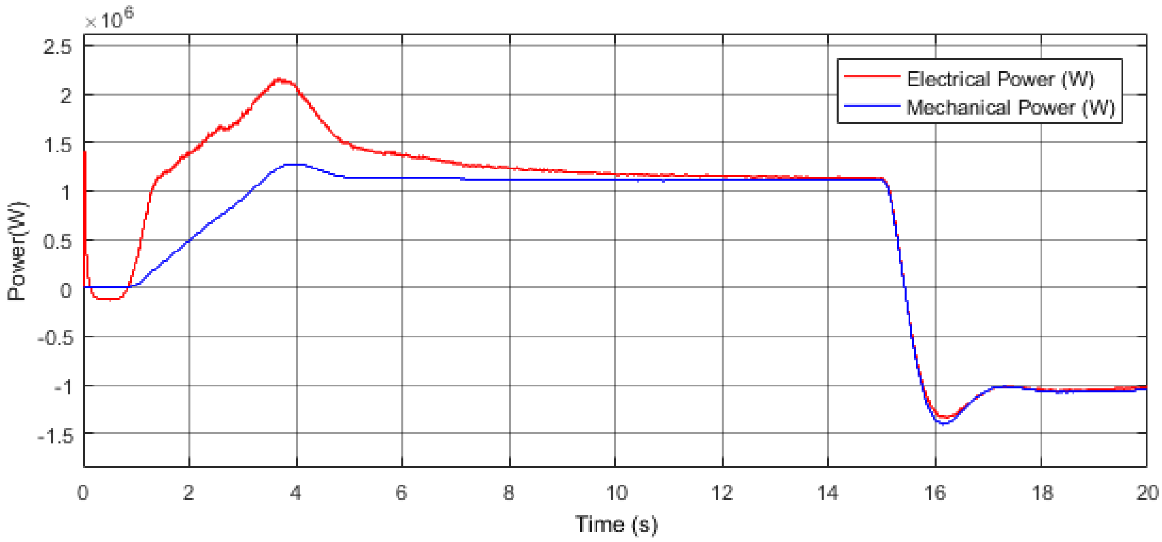

Figure 3-24: Mechanical power (blue), electrical power (red) flow into or out of the motor, 1500V and Flux = 2.0 Wb

Note that the maximum power should be constant at a value of $P = 1112kW$ (4 motors of each $278kW$). It easy to notice, with the help of figure 3-23 and 3-24, that the lower the flux is, the greater the difference between the red and blue line is at low speeds, and thus the lower the efficiency is. However when having a large amount of flux, the power the motors can deliver will be smaller at higher speeds (c.q. further in simulation time). The lower the amount of flux the flatter the power line will be at higher speeds.

When redoing these test at a DC source voltage of $2500V$ instead of $1500V$, the results will change. Now the effect of the collapsing maximum power at high speeds is not so much present anymore. So one can conclude that the effect of lowering maximum power when at high speeds is caused by a low voltage (field weakening). Remember that when discussing the parameters of the motor in section 3-5-3, it had already been discussed that this motor was made for a DC bus with a voltage of 2300 V. Which is far higher then the 1500 V used in the general train model. The effect that can be seen now is because of the field weakening region of the motor. Because in the general train a motor that should not have this effect is being used, a flux control scheme has been made. This control scheme can be seen in figure 3-27. This provides a high start efficiency and lowers the flux when the motors has a higher speed. Thereby enabling the motor to give also maximum power at high speeds. It is a workaround to cope with this problem, but it is expected that it does not influence the stability of the system.

Table 3-8: Parameters for flux test model 2

Used parameters for Flux test 2	
Source	Simple DC voltage source, no diode, 2500V
motors	4 motors connected to 1 control unit
Auxiliary supply	Not used
LC-filter	Not used
Overhead line	Not used
Rail track	Not used
Braking chopper	Not used
Torque	At t=0.3s: $T_{requested} = 99kNm$, At t=15s: $T_{requested} = -34.5kNm$

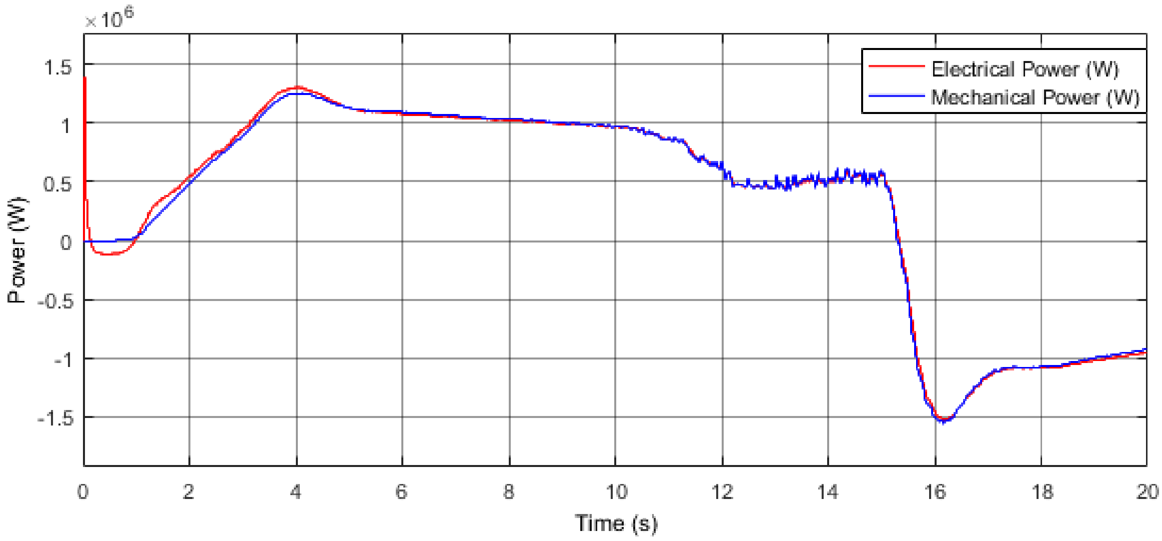

Figure 3-25: Mechanical power (blue), electrical power (red) flow into or out of the motor @ 2500V and Flux = 5.0 Wb

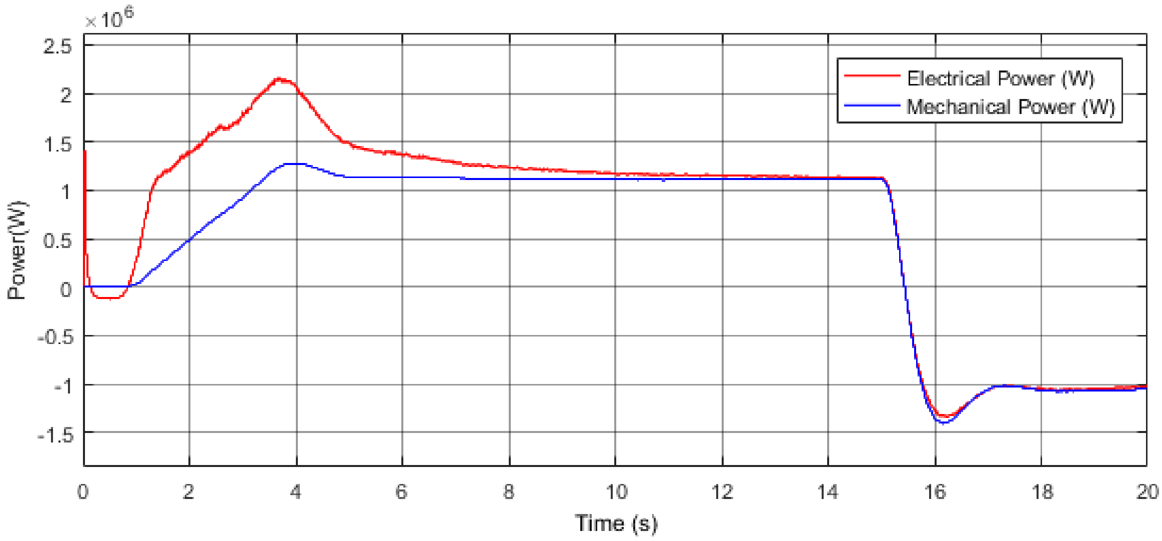

Figure 3-26: Mechanical power (blue), electrical power (red) flow into or out of the motor @ 2500V and Flux = 2.0 Wb

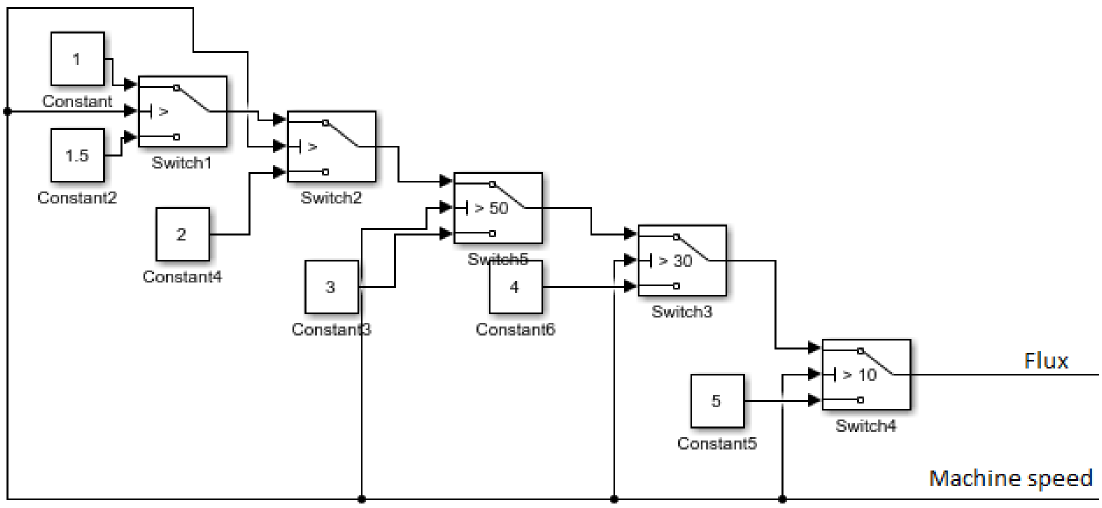

Figure 3-27: Variable flux system to provide high power at high speeds and high efficiency at low speeds, in low voltage conditions

Torque and power limiter

The power and torque limiter limits the requested torque to stop the power and torque rise above a preset value. It also employs the current limiter which has already been discussed in chapter 2-5-4. It uses various parameters to limit the current from rising to such a high amount that the voltage drops too far, it limits the current to the traction motors to a preset value and it limits the power flowing to the motors by decreasing the requested torque.

The power limitation function has been showed in figure 3-29. Here the current and power limitation function can be seen. In the torque limitation region the torque is limited to a fixed value. In the power limitation function the torque is limited in order to have a constant power. Note that a two level control has been used. Field weakening is not included because some motors used nowadays do not have the field weakening region in their usable full speed range anymore. The block can be seen in figure 3-28.

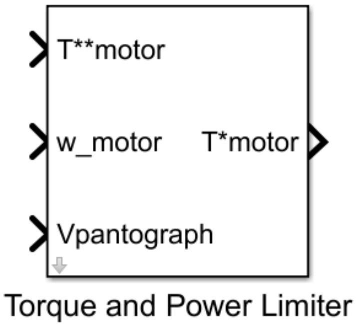

Figure 3-28: Torque and power limiter block part of the system implementation, showing inputs and outputs

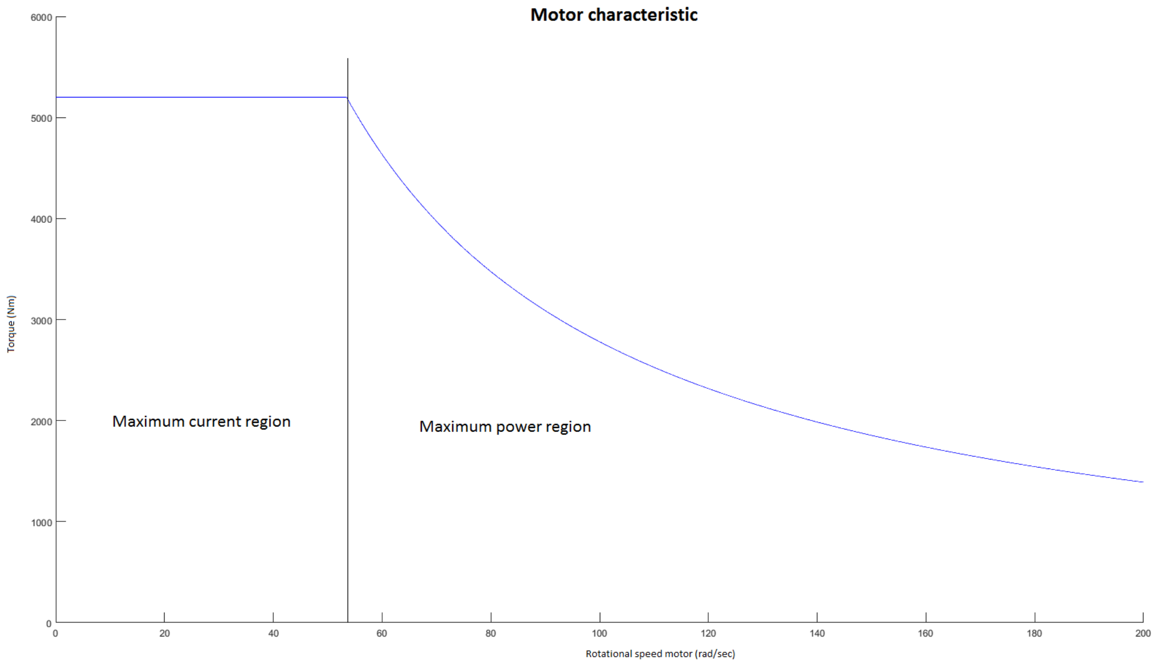

Figure 3-29: Motor characteristic

The system constructed in Simulink can be found in figure 3-30. Requested wheel torque "T**wheel" enters the block from the left, next to the rotational speed ω_{motor} and pantograph voltage. First the requested torque is multiplied with the rotational speed to form the requested power. This power is being limited by the maximum power parameter. After this limitation the requested power is divided by the pantograph voltage to make the requested current. This requested current is also being limited by the upper and lower recuperation current limit that both depends on the pantograph voltage. After this last limitation, a torque signal is reconstructed by multiplying the signal with the pantograph voltage and dividing it with the rotational speed. This forms then the signal "requested and limited torque" named "T*motor". The result of this system can be seen in figure 3-29.

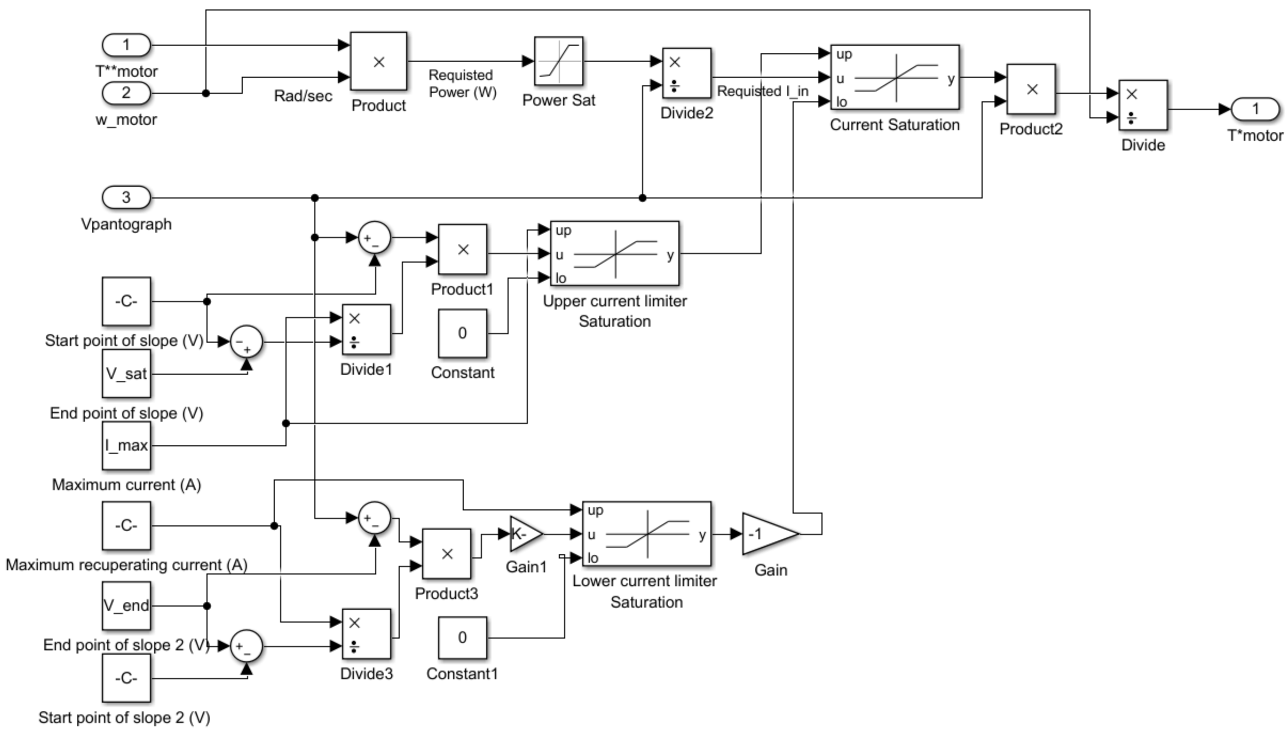

Figure 3-30: Torque limiter block

Complete traction

All the previous discussed blocks involving the motors and his controllers have been put into a block called "Complete Traction". Here 4 motors are being connected to one traction controller. This can be done because all the motors are connected to the same shaft (through port S), and have no angle difference. For that reason all the motors can use the same signal, making simulation a lot quicker while not changing the results in any way.

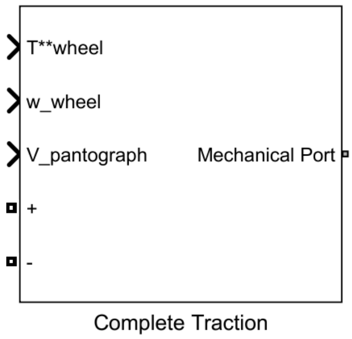

Figure 3-31: Complete traction block part of the system implementation, showing inputs and outputs

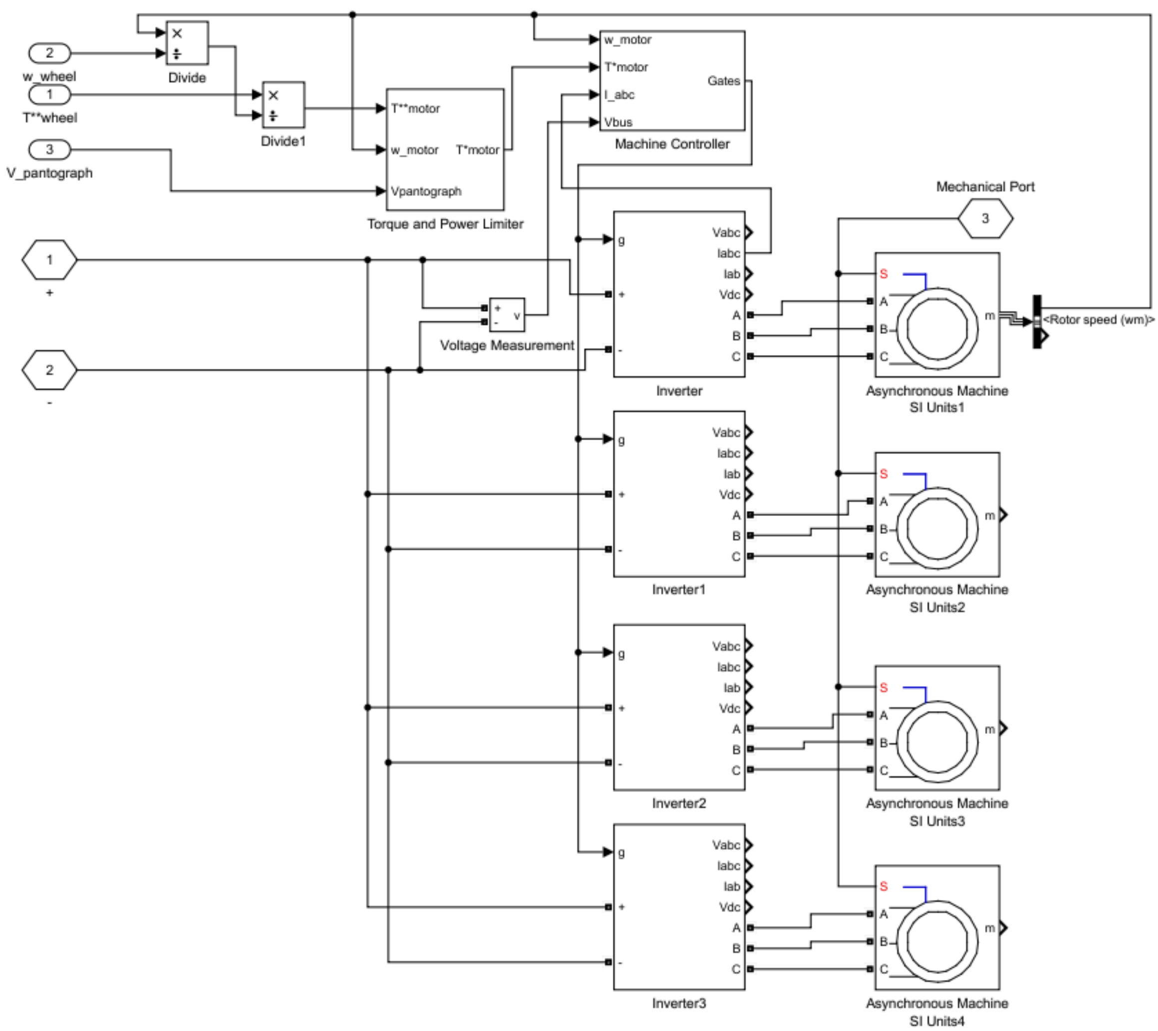

Figure 3-32: Complete traction model

3-5-4 Auxiliary supply

Multiple auxiliary supplies have been constructed. The block can be seen in figure 3-33 and the inputs and parameters can be found in table 3-9. First a realistic implementation have been made using a two stage DC/DC converter. This implementation can be seen in appendix figure 3-34. The idea behind this two stage converter is to have the last stage act as a fixed voltage source, and the fixed resistance acts like a constant power load. The first converter stage is used to help to stabilise the unstable constant power load.

The second implementation is using a current source as load. This model can be seen in appendix figure 3-35. This current source would be a perfect constant power source however when using this kind of technique in Simulink together with the inverter of the motors it will give a computation error. To fix this error the mode of Simulink has to change from accelerated mode to normal mode. Meaning a tremendous increase in computation time. So this nice implementation of a constant power source is in this model not very useful.

Figure 3-33: Auxiliary supply block part of the system implementation, showing inputs and outputs

Table 3-9: Inputs and parameters of the auxiliary supply block

Auxiliary supply	**Input**	
	+	Input positive voltage from pantograph
	-	Input ground voltage from pantograph
	Parameters	
	Auxiliary power intake (W)	Amount of power used by the auxiliary supply

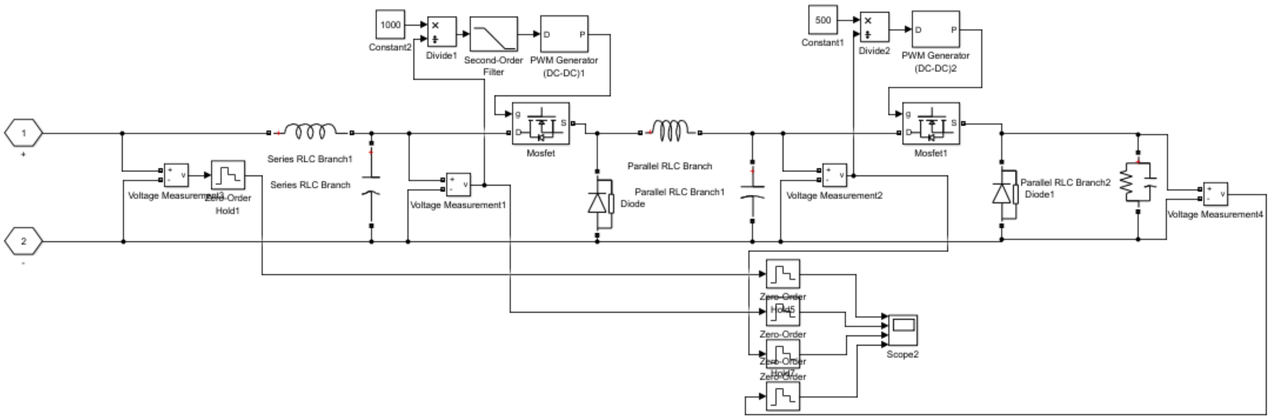

Figure 3-34: Auxiliary supply model double switching version

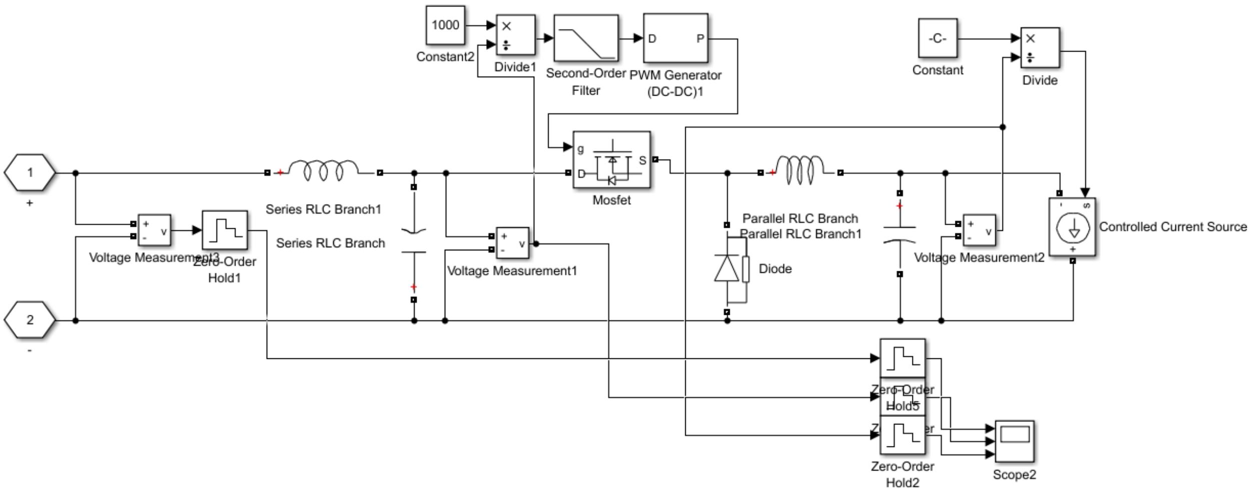

Figure 3-35: Auxiliary supply model single switching version

3-5-5 Brake chopper

Between the LC-filter block and the control system block is the optional brake chopper block. This block, figure 3-36, has the function of converting access brake energy into heat in a resistor bank. This block has only a positive and negative power inputs and a current measurement output. Parameters like resistance of the resistor bank, maximum converter frequency, activation and shutdown voltage should be filled in (table 3-10). The model of the brake chopper can be found in figure 3-37.

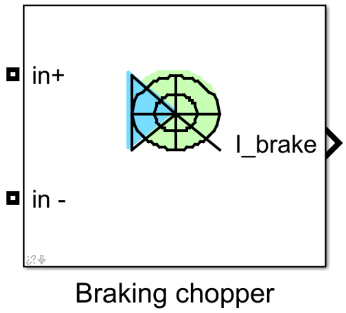

Figure 3-36: Braking chopper block part of the system implementation, showing inputs and outputs

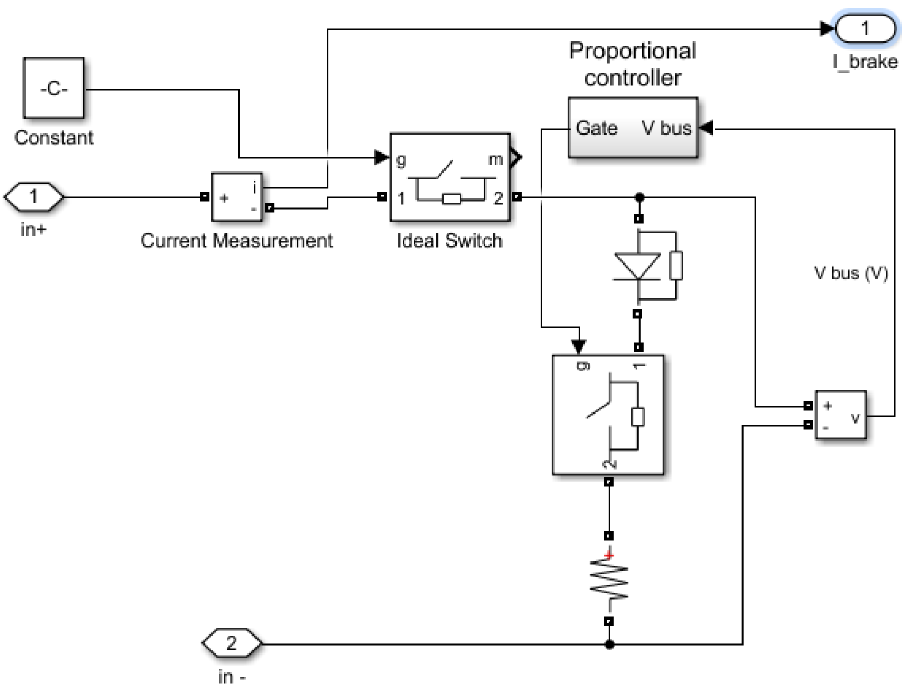

Figure 3-37: Brake chopper model

Table 3-10: Inputs, outputs of the brake chopper block

inputs	
in+	Connection to positive voltage from the bus
in-	Connection to neutral voltage from the bus
Parameters	
Enabled	Enables this block
Sample time	Sampling time (s)
R	Resistance of the resistors (Ohm)
f_max	Maximum converter frequency (Hz)
V_start	Activation voltage of the braking choppers (V)
V_stop	Shutdown voltage of the braking choppers (V)

3-5-6 Energy meter

This block is only created in order to help in the debugging of problems related to energy flows and to help create the figures. Therefore it is also not in the system overview. The idea behind this block is to measure power and energy flow in the DC bus. Next to that it also outputs the voltage and current of the DC bus. It can be placed at any place in the DC bus where one would like to measure power flow, voltage or current. The output Power measurement is filtered, with a first order low-pass filter, in order to get rid of the oscillation in current flow caused by the switching of the inverter which would otherwise make the power graph very difficult to read. This first order filter has a time constant of $50 \cdot 10^{-3} s$ The Energy meter block can be seen in figure 3-38 and the model can be found in figure 3-39. The inputs and outputs can also be found in table 3-11.

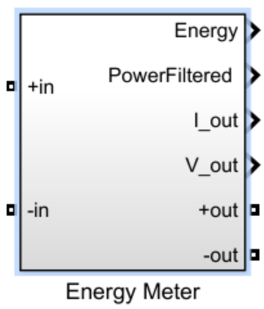

Figure 3-38: Energy meter block part of the system implementation, showing inputs and outputs

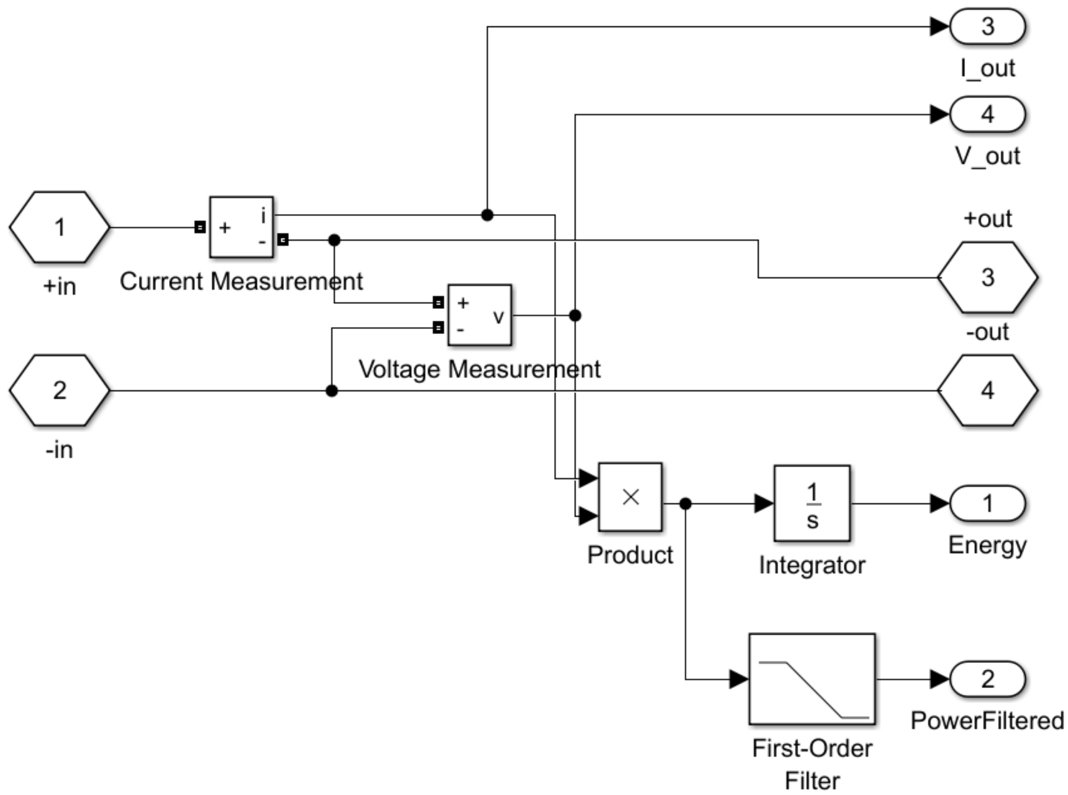

Figure 3-39: Energy meter model

Table 3-11: Inputs, outputs of the energy meter system

inputs	
in+	Connection to positive voltage
in-	Connection to neutral voltage
Output	
+out	Output positive voltage
-out	Output neutral voltage
I_out	Amount of direct current flowing (I)
V_out	DC voltage (V)
PowerFiltered	Amount of power flow, filtered with low-pass filter (W)
Energy	Energy flowed through the meter (J)

3-6 Model overview

When combining the blocks made in this chapter the DC railway model will be as in figure 3-40. The DC/DC converter is not included in this figure because otherwise the model will be too wide to show in the thesis. Also the DC/DC converter has no function in this system.

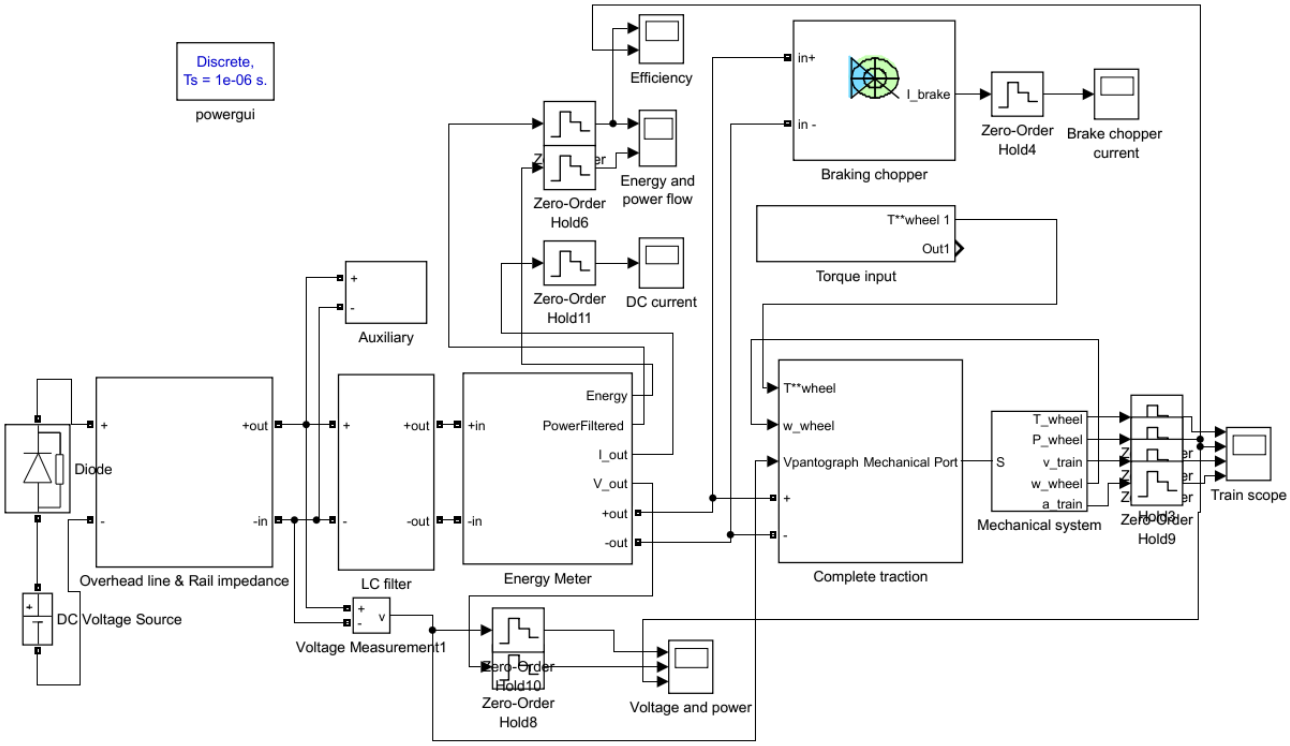

Figure 3-40: Complete simulation model of the DC railway model used in this thesis

Chapter 4

Validation

In this chapter a specific train has been taken to validate the model. To implement this train into the simulation model a few small corrections have been made to the DC railway model, which is described in chapter 3, in order to simulate the real operation of this particular train.

Every block in the system has already been validated during the design step before being used. The blocks have been tested with a simple model and later in the DC railway model for functioning and correctness in chapter 3. However when applying the blocks in a new system new or unforeseen problems can occur. Extra care has been taken to validate the most complex block, the motor with motor controller block. That part will be validated in this chapter.

The motor and motor controller itself can be validated using the method proposed in the thesis of Winterling [5] from which the motor parameters where also taken. Consequently, when replicating the measurements from that thesis one should obtain the same results as in that thesis. When looking at figure 4-1 one can see the results from the measurements done at that time. Displayed are both the simulated as the measured values of the stator frequency, the motor current of one phase and the shaft torque. The torque is divided into 3 regions because of the time fluxing of the motors take before maximum torque could be asked. Because the motors in the model of this thesis are already fully fluxed at the start of the simulation, the torque graph of figure 4-1 has been copied by changing the requested torque signal. This will be discussed later. The model made in this chapter should match the simulated values in the figure.

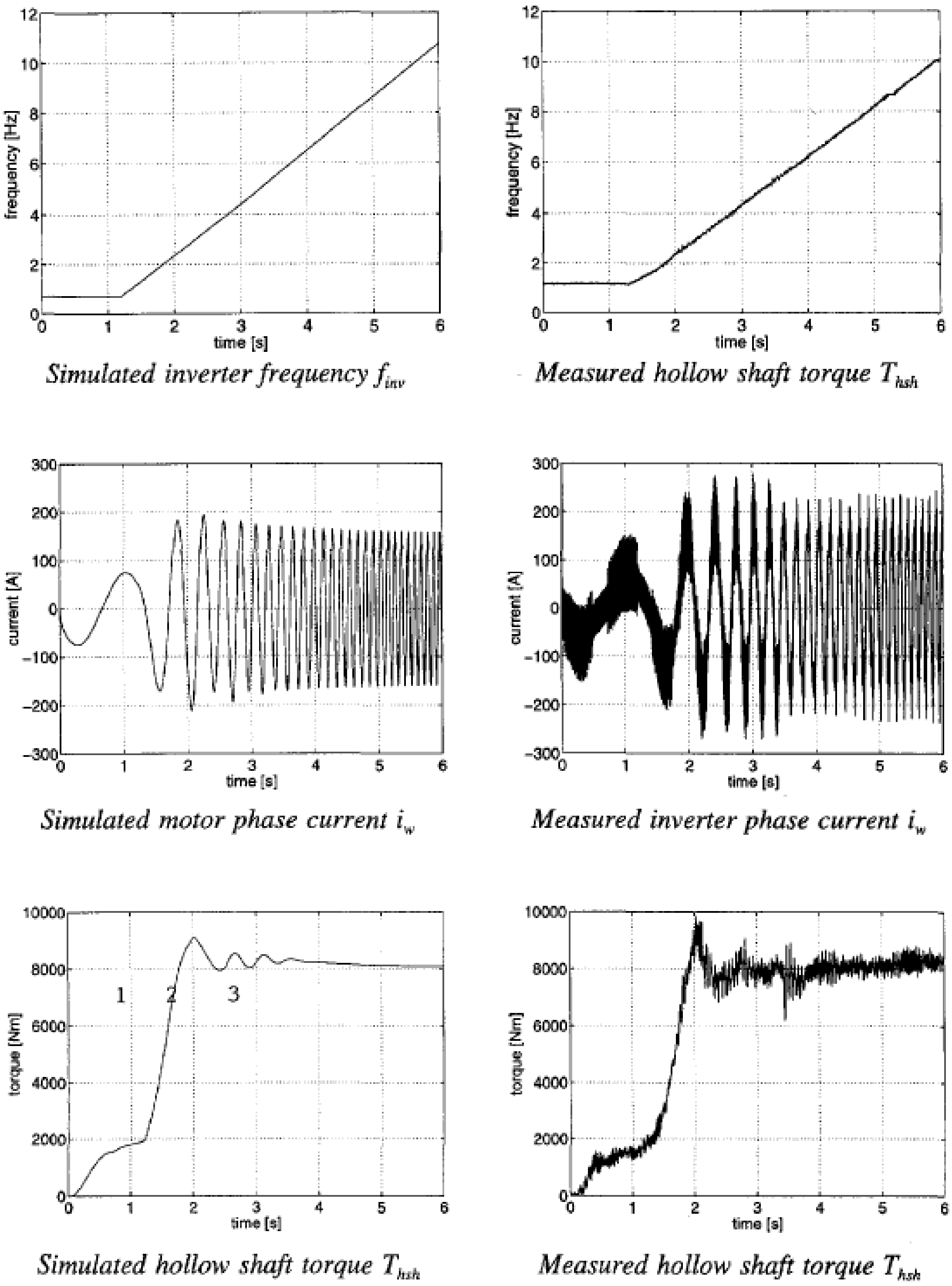

Figure 4-1: Simulation and measured data used in the past [5]

The use of the traction machines from the thesis from Winterling, made it necessary to make the typical train model less typical and more focused on the particular train used in the thesis of Winterling. The train used in that thesis is a real Dutch train, so it can be used to validate the model for the Dutch railway network. A simplified electrical schematic of this train, focused on the input filter and converter, can be seen in figure 4-2. This figure is a remake of the original scheme of the train [33]. Note that in this figure transistors are being used, while in the original thyristors have been used.

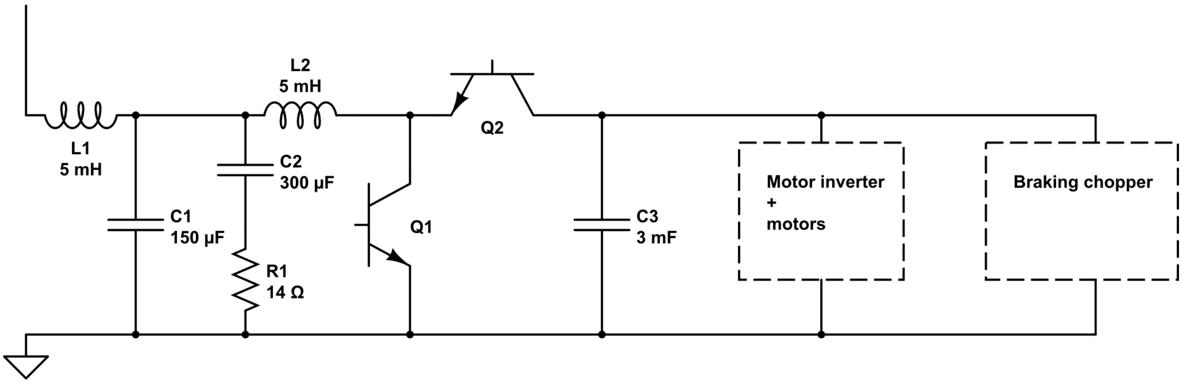

Figure 4-2: Electric scheme of the train used for validation

In the original schematic in [33], a few observations have been made:

- A DC/DC converter is used to make a DC-link voltage of around $2300V$ [5]. In normal operation it is a boost converter, but when recuperating it will be a buck converter feeding back into the overhead line.
- Thyristors are being used
- Turn-off circuits for the thyristors are being used
- The input inductance is $5mH$
- The input capacitance is $150\mu F$
- There is a CR filter present of $300\mu F$ and 14Ω
- There is a second inductance which is used as filter inductance for the boost and buck converter, value: $5mH$
- The DC-link capacitor has a value of $3mF$
- The brake resistor, which can be seen on the right of the schematic, has a value of 4Ω and is connected in parallel to the motor inverter

The model had to be been changed to implement this specific train. The new model can be seen in figure 4-3.

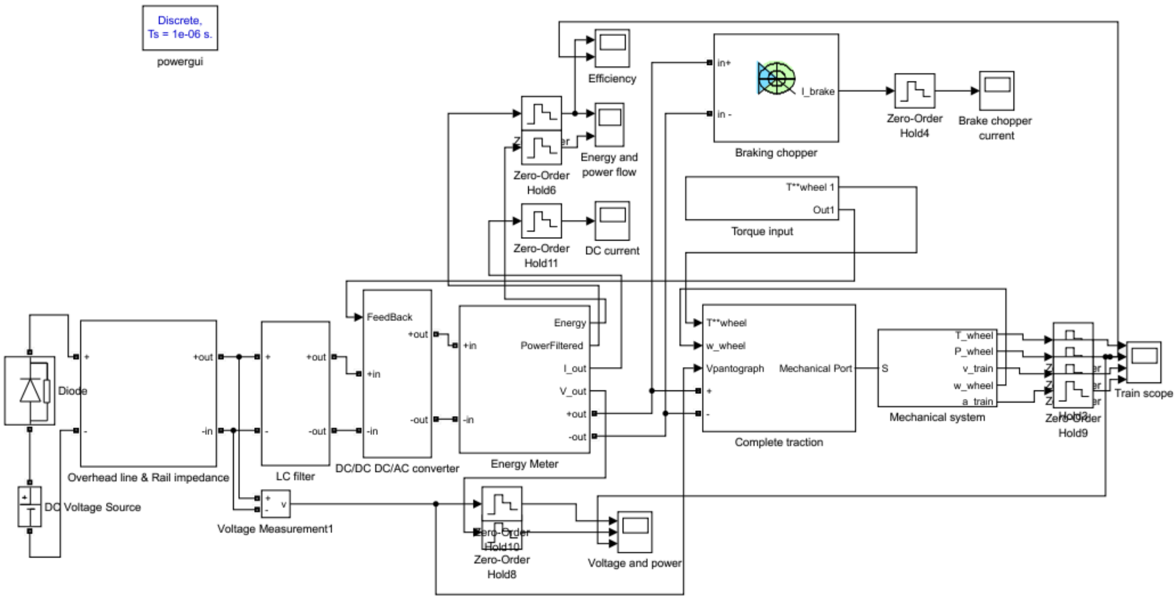

Figure 4-3: Simulation model used for validation

4-1 LC-filter

The LC-filter block had to be changed to reflect on the LC filter that can be found in figure 4-2. In this filter configuration next to the LC filter also a RC filter is being used. In figure 4-4 the new model implementation of the filter can be seen. The simulation resistances are just there to avoid compiling errors. The inductance has got a R_{ESR} value of $R = 28m\Omega$. The other values where taken out of figure 4-2.

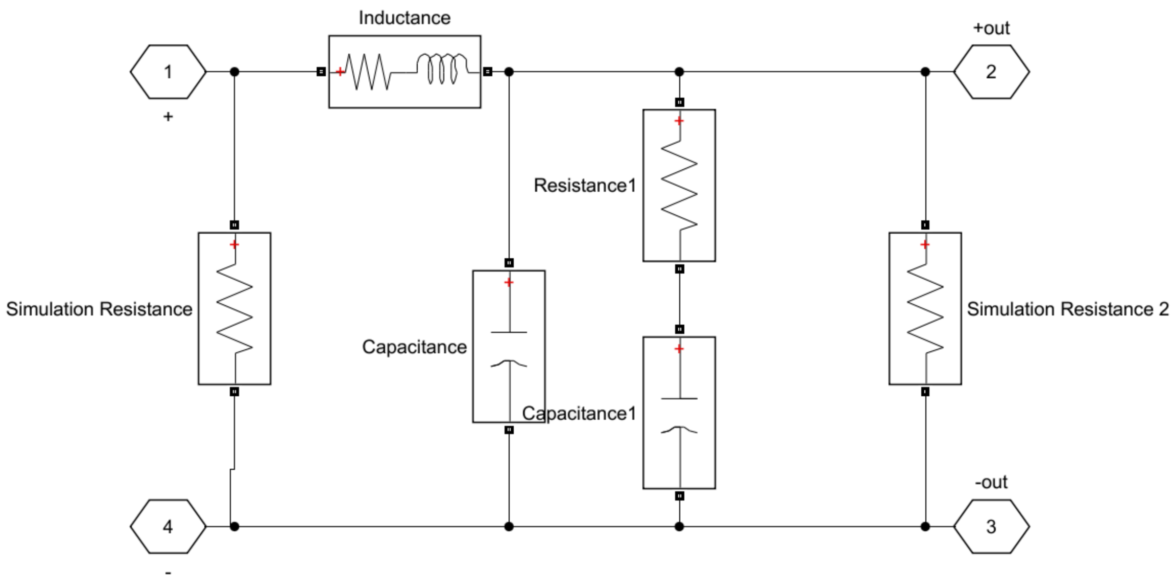

Figure 4-4: LC-filter used for validation

4-2 DC/DC converter

A DC/DC converter has been modelled that will switch from boost function to the buck function when a recuperation signal is made high. The output voltage of the boost converter is set to $2300V$ assuming the converter is in Current Conduction Mode (CCM) and the switch is ideal. In the simulation this will mean a nominal DC link voltage of around $2300V$ when loaded. The boost converter is turned off when the voltage is above $2400V$, because otherwise the voltage will continue to rise because the converter is not in CCM mode of operation. The buck converter, which is used to feed back energy into the pantograph, measures the voltage on the overhead line side of the converter and divides this value by $1950V$. Now the grid has a somehow fixed voltage and the motors are generating the power. The control of the buck converter is in reality not as easy as $D = \frac{V_{out}}{V_{in}}$. However it provides a very simple and computational easy way to feed energy back into the grid. The function of feeding energy back into the network will not be used because it is not part of the validation. So the simplification does not have an impact on the results. A external supplied signal, from the torque signal generation block has been used to set the converter in boost or buck mode.

The DC/DC converter scheme can be seen in figure 4-5.

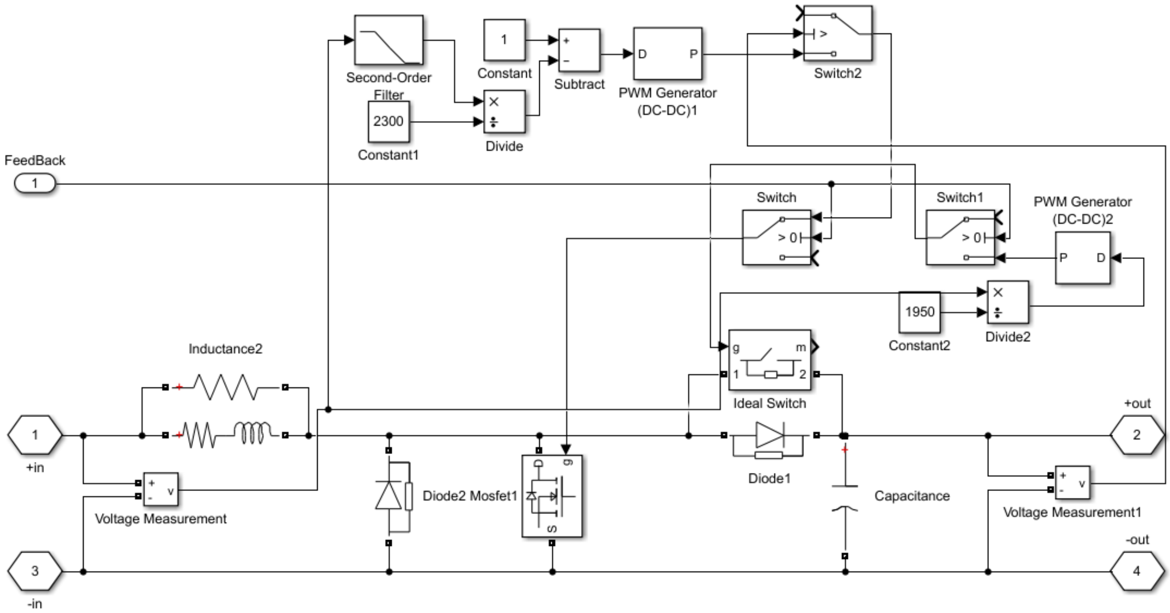

Figure 4-5: Scheme of the DC/DC converter used for validation

4-3 Torque input

In order to simulate the same wheel torque as in the thesis of Winterling, which can be seen in figure 4-1, the torque signal generator has to be changed. In figure 4-6 the new torque signal generating scheme can be seen. The output of this generator can be seen in figure 4-7. Note that the first second is being used to initialise the system and stabilise the voltage and is therefore eliminated from every figure in this chapter.

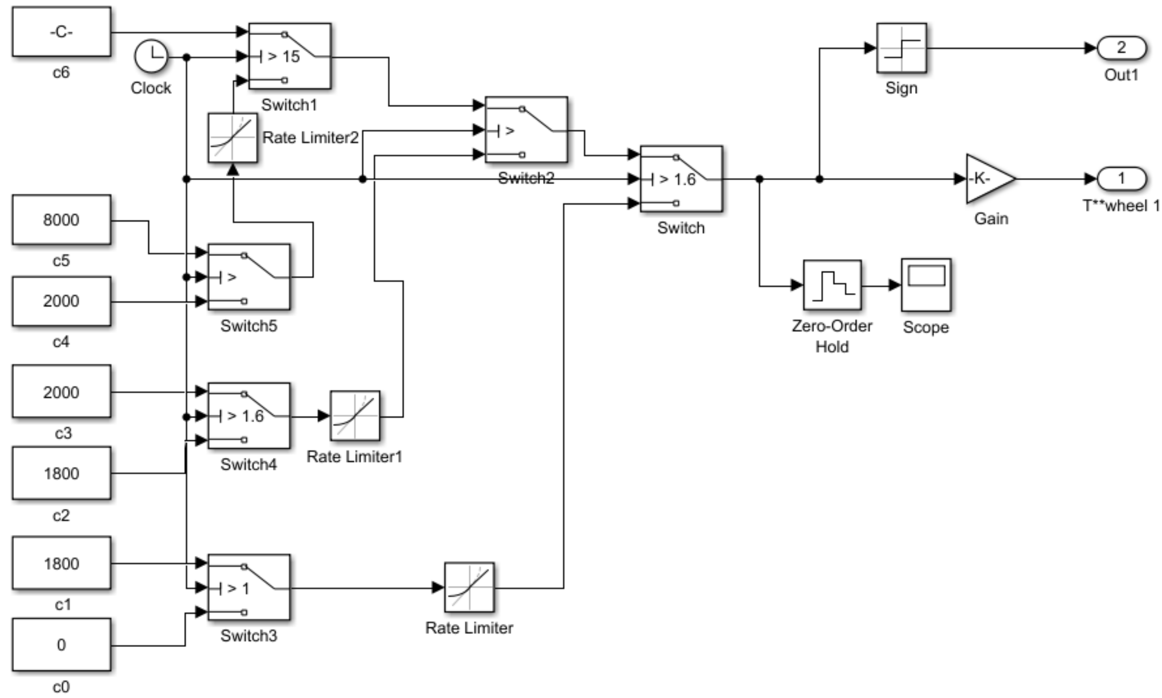

Figure 4-6: Scheme of the requested torque used for validation

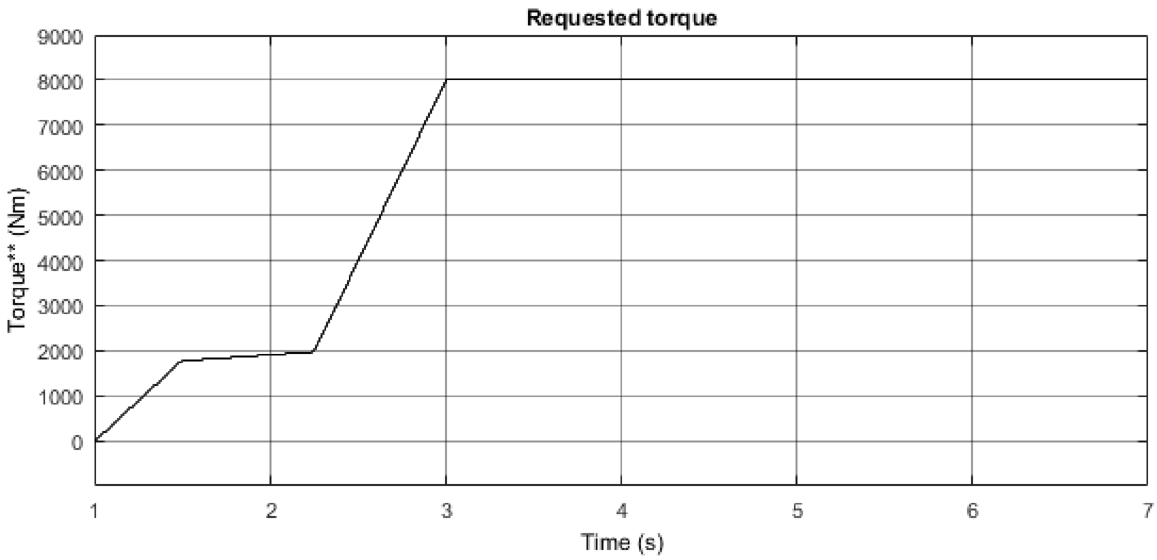

Figure 4-7: Graph of the requested torque used for validation

4-4 Motor controller

In order to get the same measurement in the simulation compared to the measurements in the thesis of Winterling[5], some parameters have been derived from the that thesis. The following parameters have been used next to the motor parameters which can be found in section 2-5-4:

- $T_{motor} = 2000Nm$
- $mass = 92000kg$
- $D_{wheel} = 0.92m$
- gearbox ratio = 69/16
- 4 motors per train set

Note that in the thesis of Winterling, in figure 4-1, a minimum stator frequency can be seen. This however can not be implemented in the model made in this thesis. Therefore the frequency is expected to be of in at least the first second.

4-5 Validation of motor control

The motor current, which will be compared to the motor current in figure 4-1, can be seen in figure 4-8. One should note that the time scale of figure 4-8 has a offset of 1 second. This second was needed to get the system in steady state. When comparing those two figures it can be concluded that they look like each other. The amplitude and the frequency, as well as the torque figure looks like each other. The difference in frequency is low. When counting the amount of peaks in 1 second one can get an idea about the stator frequency. It has been proven that the system work like each other. Because the system in the thesis of Winterling is verified the motors and motor controller has been verified in this thesis.

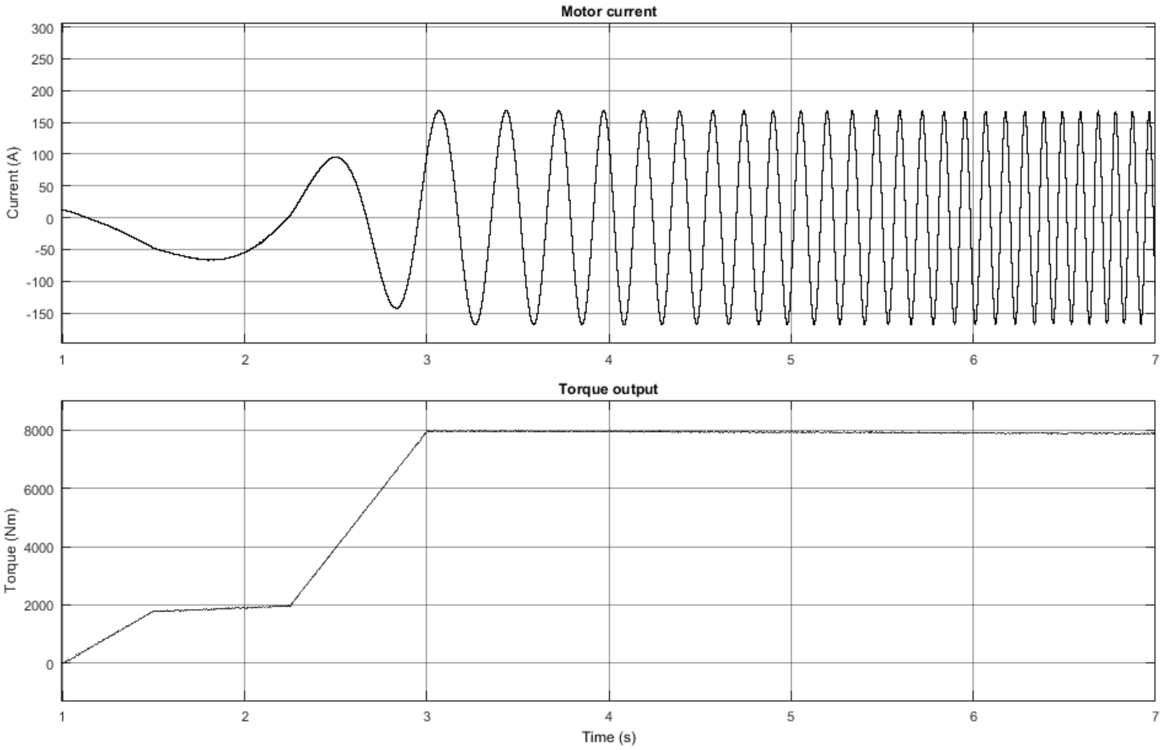

Figure 4-8: Motor stator current and shaft torque

Chapter 5

Simulations

In this chapter the requirements of the simulations are discussed. First the term "stable" is discussed, after that the necessary simulation methods are discussed. In this thesis two approaches will be used. The first approach is the constant power controlled general train model, as discussed in the previous chapters, this train will be simulated in chapter 6. The second approach is one where the constant power control is omitted and replaced by a simple PWM generator to eliminate the influence of constant power control. This system will be simulated in chapter 7. The basic however is still the general train model.

5-1 Determination of a "stable system"

A unstable system is a system that will give a infinite output while a finite input is given [34]. In an electrical model a system that is unstable has for example an oscillating voltage level that is increasing in amplitude over time. In appendix A one can see the phenomena of a resonance circuit.

In this thesis, three requirements have been defined to determine if a system can be called stable:

5-1-1 Requirement 1: Pantograph voltage

According to the norm used in the Dutch railway, NEN EN 50163, the voltage **in front of the LC-filter, at the pantograph**, should meet the following requirements:

- Lowest voltage: 1000 V
- Nominal voltage: 1500 V
- Highest permanent voltage: 1800 V
- Highest voltage over 5 minutes: 1950 V
- Highest voltage over 20 ms: 2538 V

5-1-2 Requirement 2: Maximum oscillation voltage

For this requirement the maximum peak to peak voltage oscillation for any point in the system has been arbitrarily set at $300V$ averaged over 5 oscillation periods. It is expected that some high amplitude resonance should be damped to a ripple less then $300V$ peak-to-peak, when having a stable system. Next to that, the resonance peak voltage should not be more than $1000V$ at all times. The voltage on **any point in the system** should meet the following to pass the second requirement:

- $V_{peak-peak} < 300V$ for 5 periods averaged
- $V_{peak-peak} < 1000V$

5-1-3 Requirement 3: Maximum power output oscillation

The maximum voltage after the LC-filter is not specified. This because it is part of the train itself, not the railway system. The voltage after the LC-filter can fluctuate a lot when having a constant power control. This does not immediately mean an unstable system, one may be interested in the power ripple or torque ripple of the motor output. A maximum torque/power ripple, measured at the output of the motor, of 15% has been arbitrarily chosen to pass for the third requirement. This output signal will be damped with a second order low-pass filter with a natural frequency of 10 Hz and a damping ratio of 0.707 before measuring the output power or torque ripple.

5-1-4 Classification of stability

In this thesis the results of the simulation will be classified according to the specific requirements which they have passed. A system can be named fully stable, output power/torque stable or unstable.

- Fully stable: meets all requirements above
- Output power/torque stable: meets requirement 1 and 3, the voltage after the LC-filter has a too high ripple to have a fully stable system
- Unstable system: meets none or only requirement 1 of the requirements

When having an "output power/torque stable system" the system is stable enough to keep the motors turning without too much power ripple, however that does not mean that large voltage ripple after the LC-filter is acceptable. High voltage fluctuations can cause high capacitor currents to flow, which can cause the capacitor to overheat or exceed specifications. So while the name of the classification carries the word "stable" in it, the voltage on the capacitance is unstable.

Note: During initialisation of the model the model does not have to meet the requirements from above. The system should be in steady state as soon as possible after beginning of the simulation. Around half a second, depended on the particular simulation, has been given to the system to get in a steady state before the motors are put on. After that time the requirements are checked.

5-2 Determination of the key parameters in this model

In this section the different simulations are discussed and key parameters are determined.

5-2-1 The size of the capacitance in the LC-filter

In this simulation the effect of changing the value of the capacitance on the stability of the system is simulated. Important outputs are voltage and power flow. There should be a capacitance value at which the system is fully stable. Two simulations will be done, a simulation with a ten times smaller capacitance and a simulation with a ten times larger capacitance than the standard simulation model.

5-2-2 The inductance and resistance of the overhead line

It is expected that a greater distance from train to substation, with consequently a larger inductance in the feeding line, lowers the stability. This because the voltage variation is higher due to more impedance between train and substation. A distance of 10 km will be set and simulated. Next to that, it will be simulated whether the resistance or the inductance is the destabilising effect in the overhead line. This will be done by simulating with only one of the two, only resistance or only inductance, and comparing the results.

5-2-3 The influence of doubling the overhead line voltage

Doubling the voltage of the network to 3 kV has been discussed for several years. Next to the advantages of lower currents and consequently lower power losses during transportation of the energy to the train, there could also be an advantage be found in the stability of the system. With the same component values of the inductance and capacitance, at the same resonance frequency, more power can be stored in the capacitance because of the higher voltage. However one should note that doubling the voltage capability of a capacitor means quadrupling the volumetric-size of the capacitance. In figure 5-1 one can see that 3 kV systems are far more widely used than the 1500 V system in the Netherlands.

For the reason described above, 2 simulations will be run. One with the same capacitance and inductance values as the standard model, and a simulation with corrected capacitance and inductance values according to energy storage. It is expected that higher energy storage in the capacitance helps keeping the system stable.

For this simulation the voltage requirements for a stable system are doubled because the system voltage is also doubled. So for the 3000V network the following requirements should be met in order to call the system fully stable.

- Lowest voltage: 2000 V
- Nominal voltage: 3000 V
- Highest permanent voltage: 3600 V

- Highest voltage over 5 minutes: 3900 V
- Highest voltage over 20 ms: 5076 V
- $V_{peak-peak} < 600V$ for 5 periods averaged
- $V_{peak-peak} < 2000V$

5-2-4 The influence of a braking train on an accelerating train

A train during braking could be represented by a negative resistance. To see what the stability of a system with two trains is, one braking train and one accelerating train is simulated. In the model a train with distance of $-0.5km$ from the substation with a initial speed of $34m/s$ is braking with a torque set-point of $-99kNm$. At a distance of $0.5km$ a train is accelerating from standstill with a torque set point of $99kNm$. Voltage and power fluctuations of both trains should be measured to see if a trains effects another trains stability.

5-2-5 The influence of adding a RC damping branch

In this simulation the design of the LC-filter will be slightly changed and a RC damping branch will be added. The effect of such damping branch will be determined and discussed.

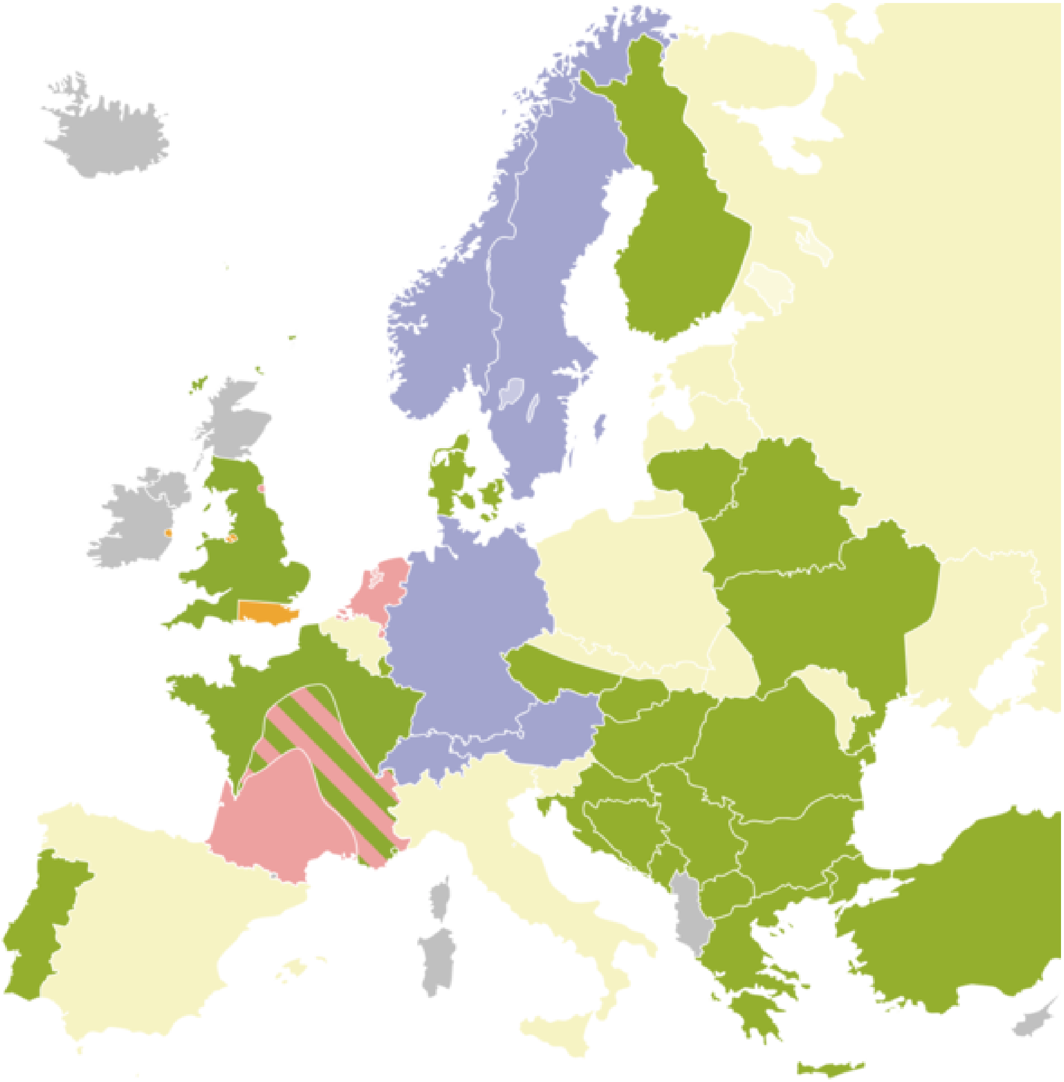

Figure 5-1: Voltages of electrified track per country[6]. Orange: 750 V DC, Magenta: 1500 V DC, Yellow: 3 kV DC, Blue: 15 kV 16.7Hz, Green: 25 kV 50Hz, Grey: not-electrified

Chapter 6

Results first approach: Constant Power Control

In this chapter the results of the first approach are presented. The general train is being used, instead of the train used for validation. The overall system can be seen in figure 6-1. A simple DC-source with series diode is used to simulate the substation. It has been proven that the 600 Hz harmonic component of the 12 pulse rectifier is highly damped in the LC-filter as can be seen in figure 3-2. To speed up the simulation it is chosen to exclude the substation from the system. Since of the 600 Hz and higher order components cannot pass the LC-filter, no change in results are expected in the voltage after the filter. There can be some influence in the voltage on the pantograph but because of the low ripple from the substation no big change in results is expected because of that.

Also the auxiliary supply has not been implemented in this general train model. Because this research is about optimising the input filter of the traction installation, and around 95% of the peak constant power load is in the traction, the focus was put onto the traction power.

In each simulation the voltage is measured at the point of the pantograph (named ”Pantograph voltage”) and over the capacitance of the LC-filter (named”Voltage after LC-filter”). Also the mechanical power will be shown. Note that the mechanical power is not equal to the electrical power, because of the loss in power due to efficiency.

Note: in the schematic, figure 6-1, ”Zero-Order Hold” blocks can be found. These blocks are just there to decrease the sampling rate of the scopes which are being fed by the output of these blocks. This to decrease memory usage. It does not influence, numerical, the results.

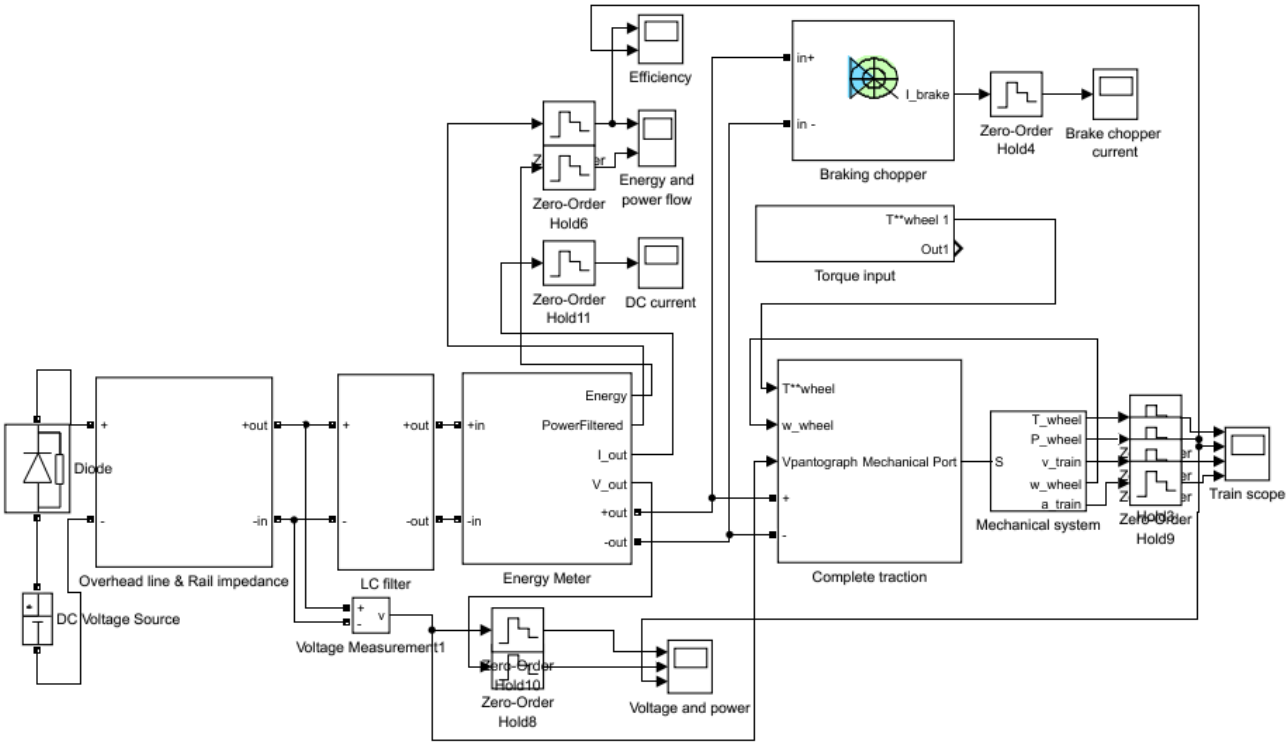

Figure 6-1: Standard simulation model of the general train used in this thesis

The simulation results will be tested according to the following requirements, which where discussed in chapter 5:

1. Pantograph voltage
2. Maximum oscillation voltage
3. Maximum power output oscillation

6-1 Simulation of the effects of the key parameters on the system

In this chapter the simulations described in chapter 5 are performed. The typical torque at the wheels, power at the wheels, train speed and acceleration can be seen in figure 6-2. The motors are ramped up to a torque set point of $8.9kNm$ from $t = 0.50s$ to $t = 1.15s$. At $t = 3.25s$ the speed is high enough to have maximum rated power flowing in the motors at that constant torque point and the torque is decreased in order to have a constant power at the maximum power rating of the motors. The train speed is increased from 0 to almost $15m/s$ in 10 seconds. The simulation ends at t = 10 sec. This cycle will be used for all of the following simulations.

The simulations are done by changing the parameters and simulate them after the change.

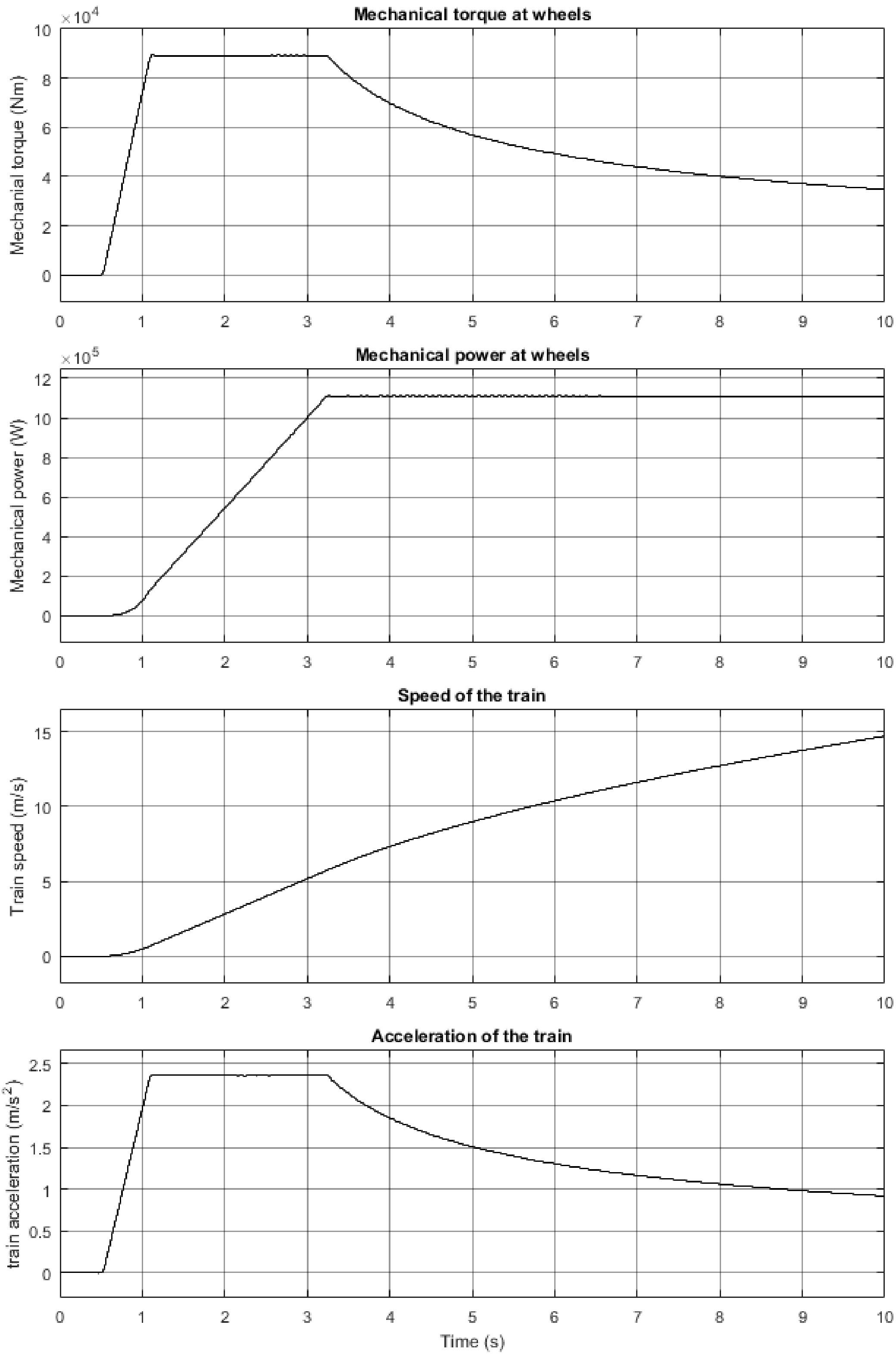

Figure 6-2: Torque at the wheels, power at the wheels, train speed and acceleration for the standard simulation cycle

6-1-1 Simulation 0: Standard general train model

The first simulation being done is the simulation with a complete system. This simulation will be set as standard, the simulations hereafter will be compared with this simulation to see if the stability is improved or not. It has a capacitance value of $10mF$ in the LC-filter and a distance from substation to train of half a kilometer. The braking chopper is turned on to help the system to stabilise. The parameters used can be found in table 6-1.

Table 6-1: Parameters for general train model simulation

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $C = 10mF$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

In figure 6-3, the voltage graph can be seen. The motor mechanical power is increased from 0 W to 1.1 MW in less then 2.5 seconds. When the power of the motors is larger than the maximum power (in this case 82 kW) that can be calculated with the formula discussed in 1-4-3, the system starts to oscillate. It is clearly visible that the voltage after the LC-filter is unstable. However the voltage on the pantograph is according to the specifications. When looking at the mechanical power output, the system is also according to specifications. There is hardly no ripple in the power output of the motors. Consequently this system can be called "output power/torque stable". With some small improvements in the control of the traction system or in the electrical system this system should be able to be made stable.

With the information in the figure, the following can be said:

Table 6-2: Results of test 0

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
0	Standard	1760	75	700	Yes	1.11 MW, <1%	Power output stable

The outcome of this first simulation with the standard parameters is that this system meets requirement 1 and 3 but fails requirement 2 because the ripple after the LC-filter is too high. This ripple is around 700 Volts instead of the maximum 300 Volts. So this system is labelled "Power output stable".

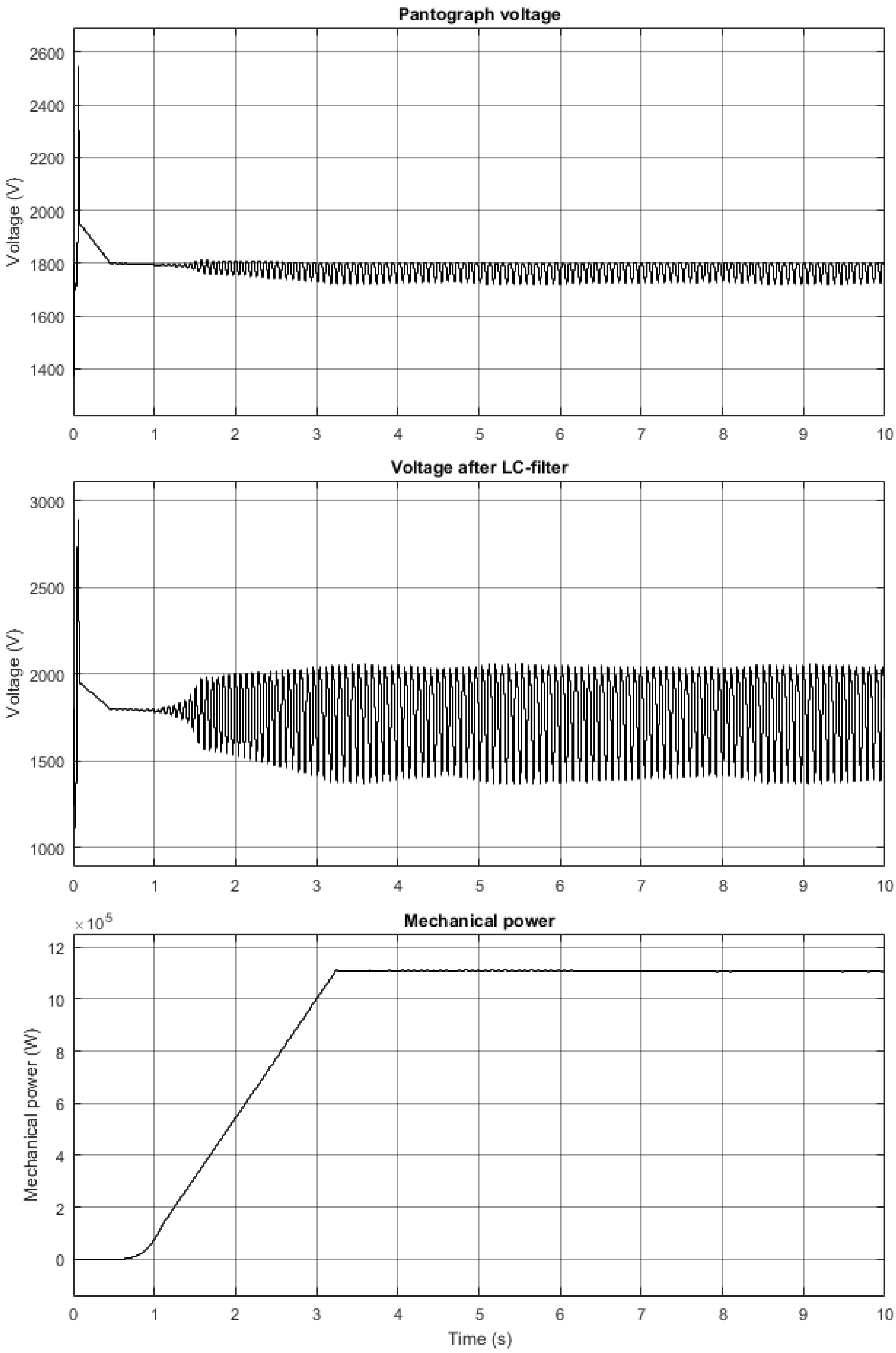

Figure 6-3: Voltage and power graph of the standard general train system simulation

6-1-2 Simulation 1: Standard model with higher capacitance

In this simulation the capacitance of the LC-filter is made 10 times larger, namely $100mF$. The following parameters have been used:

Table 6-3: Parameters for general train model simulation without auxiliary supply

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $\boldsymbol{C = 100mF}$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

When comparing the results of this simulation with the standard simulation (simulation 0), it can be seen in figure 6-4 that the voltage ripple after the LC-filter is now smaller then it was. So a larger capacitance value helps to lower the amplitude of the voltage oscillation. With a 10 times larger capacitance there is still a significant voltage oscillation present with a peak to peak value of $\approx 400V$. Note that the frequency of the resonance is now much lower then it was in the standard simulation because of the higher capacitance value. Also note that the point of power at which the system becomes unstable is also 10 times larger then the standard simulation, according to the formula in 1-4-3. So the system should get unstable at $P = 840kW$.

Table 6-4: Results of simulation 1 small capacitance

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
1	$C = 100mF$	1770	60	400	Yes	1.11 MW, <1%	Power output stable

The system meets requirement 1 and 3 but fails requirement 2 because the ripple after the LC-filter is too high. This ripple is around 400 Volts instead of the maximum 300 Volts. So this system is labelled "Power output stable".

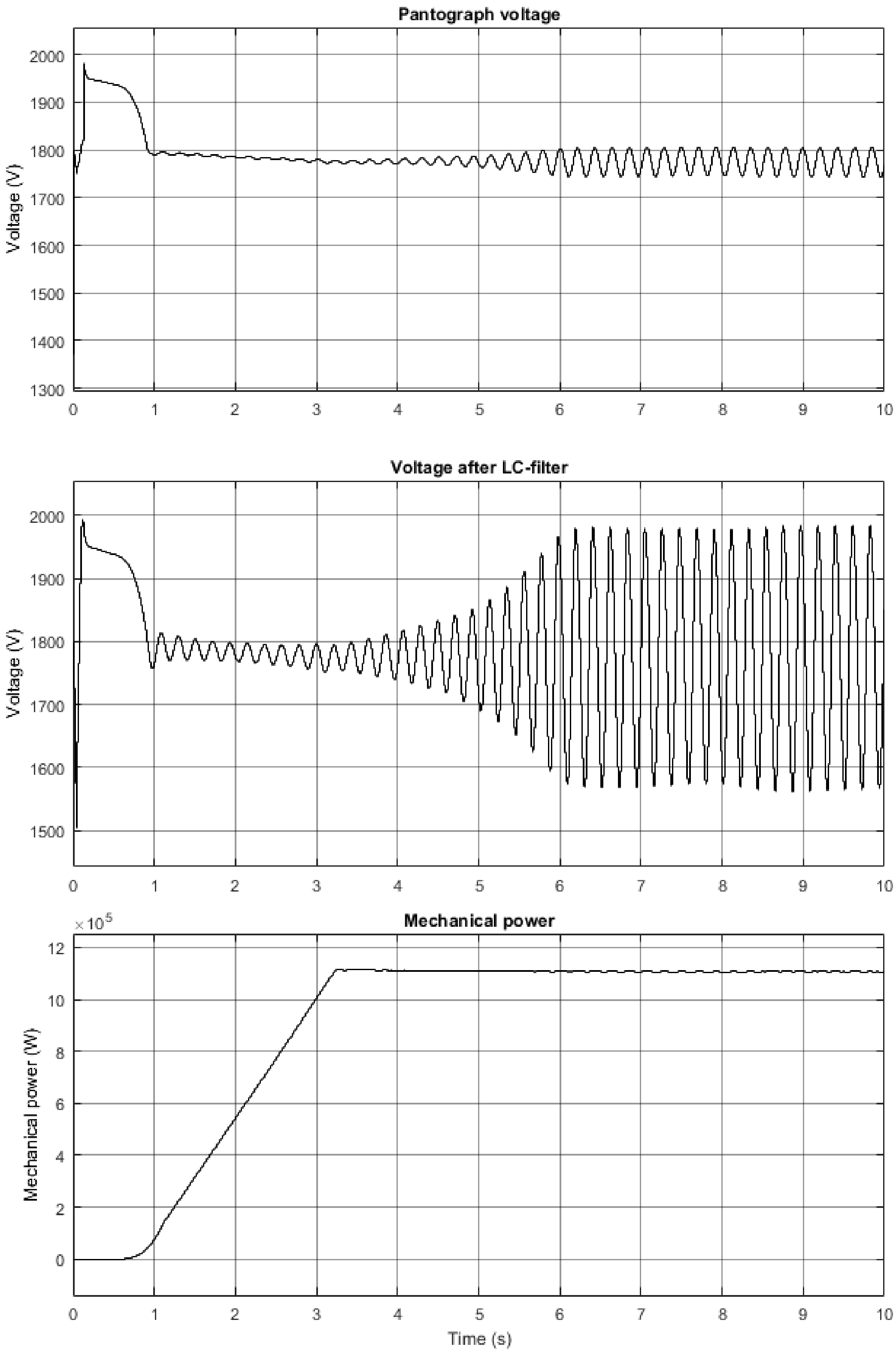

Figure 6-4: Voltage and power graph of the general train system with $C = 100mF$

6-1-3 Simulation 2: Standard model with low capacitance

In this simulation a small capacitance value will be used. It is expected that the ten times smaller capacitance will make the system unstable at the voltage after the LC-filter. The results from this simulation can be seen in figure 6-5.

The following parameters have been used:

Table 6-5: Parameters for simulation with low capacitance

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $\boldsymbol{C = 1mF}$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

When looking at the results and comparing it with the results from the basic system in figure 6-3 one can see that the voltage oscillation is far greater now. This because of the less energy that can be stored in the capacitance. According to the formula in section 1-4-3, the point of power at which the system should get unstable will be $P = 8.4kW$, which is almost immediately after start, which can also be seen in the figure. In the figure also some zoom-in graphs can be seen. It can be seen that the braking chopper, which is activated when voltage increases above 1950 volts, has some large effect on the graph. Not only is the maximum voltage that can be seen in the zoom-in clearly capped, also a strange effect in the frequency can be seen. This could be further researched.

The following results can be seen in the figure:

Table 6-6: Results of simulation 2 low Capacitance

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
2	$C = 1mF$	1750	100	900	Yes	6.5 MW, 8%	Power output stable

It is clear that the voltage oscillation is far too high to meet requirement 2. The voltage on the pantograph is within specs and the power ripple is also within tolerance. Therefore this system is called "Power output stable". Note that the power output is limited.

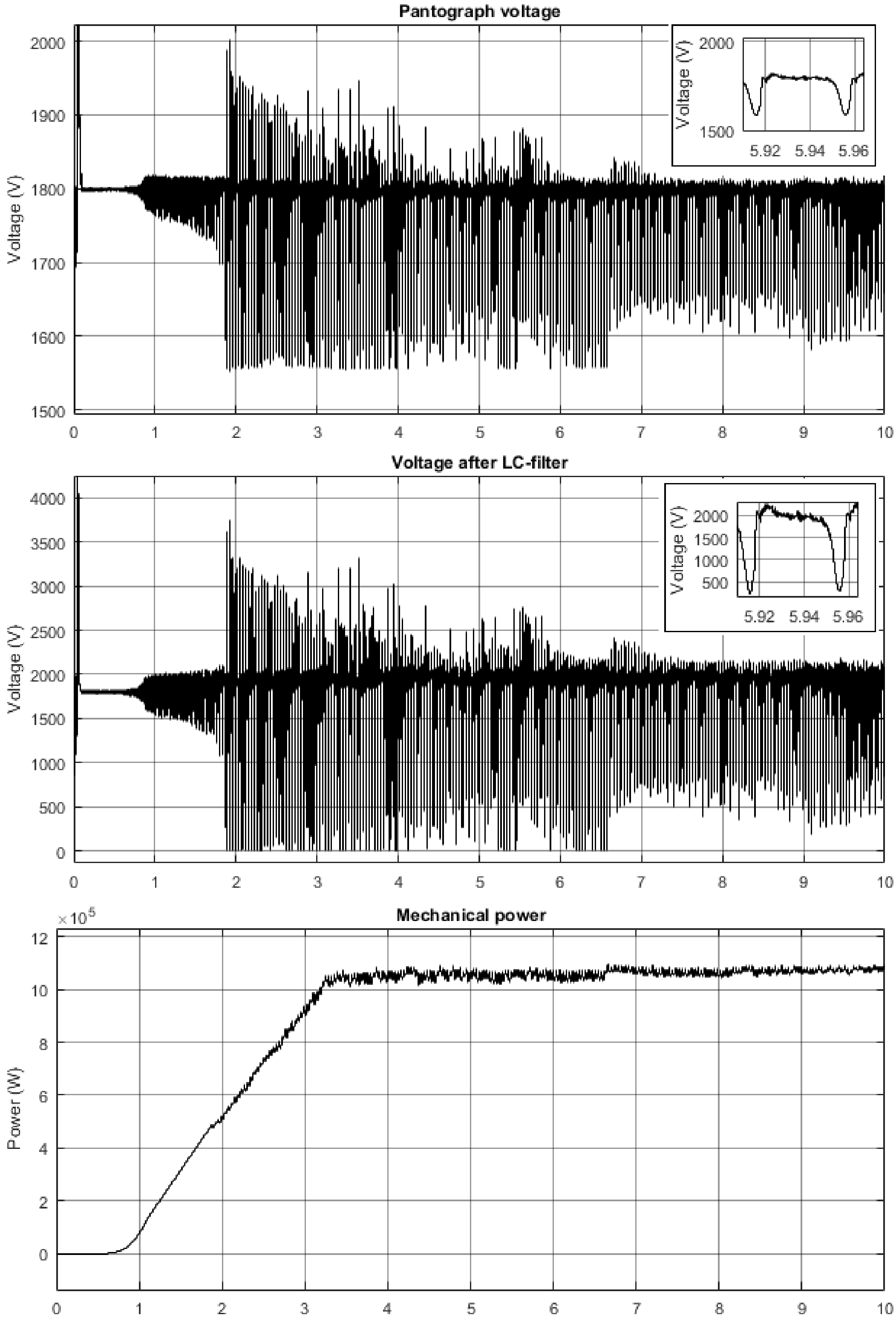

Figure 6-5: Voltage and power graph of the general train system with $C_{LC} = 1mF$

6-1-4 Simulation 3: Standard model with low inductance

In this simulation a small inductance value will be used. It is expected that the ten times smaller inductance will make the system more stable at the point of the DC-link. The results can be seen in figure 6-6.

The following parameters have been used:

Table 6-7: Parameters for simulation with small inductance

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $C = 10mF$ and $\boldsymbol{L = 1mH}$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

When comparing the results from this simulation with the previous simulation with a small capacitance (figure 6-5), it can be seen that the system is much more stable now. So for stability it is better to use a small inductance and high capacitance. When comparing this simulation with the basic simulation in figure 6-3, it can be seen that the stability is also better here. So proving the idea of having a low inductance is better for stability. This can also be seen in the formula in section 1-4-3. A ten times smaller inductance means a ten times larges maximum stable P (note that the inductance of the overhead line is also in this formula, so in this test the maximum stable power is not ten times larger). Filling in the formula gives a maximum stable power point of $P = 0.397MW$. Which is indeed at the point in the graph where the oscillation starts.

The following results can be seen in the graph:

Table 6-8: Results of simulation 3 Small Inductance

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
3	$L = 1mH$	1775	250	450	Yes	1.11 MW, <1%	Power output stable

With this small inductance the voltage ripple after the LC-filter is far lower now. It is almost low enough to be called stable. This simulation meets requirement 1 and 3. But still fails requirement 2. Therefore it is also called "Power output stable".

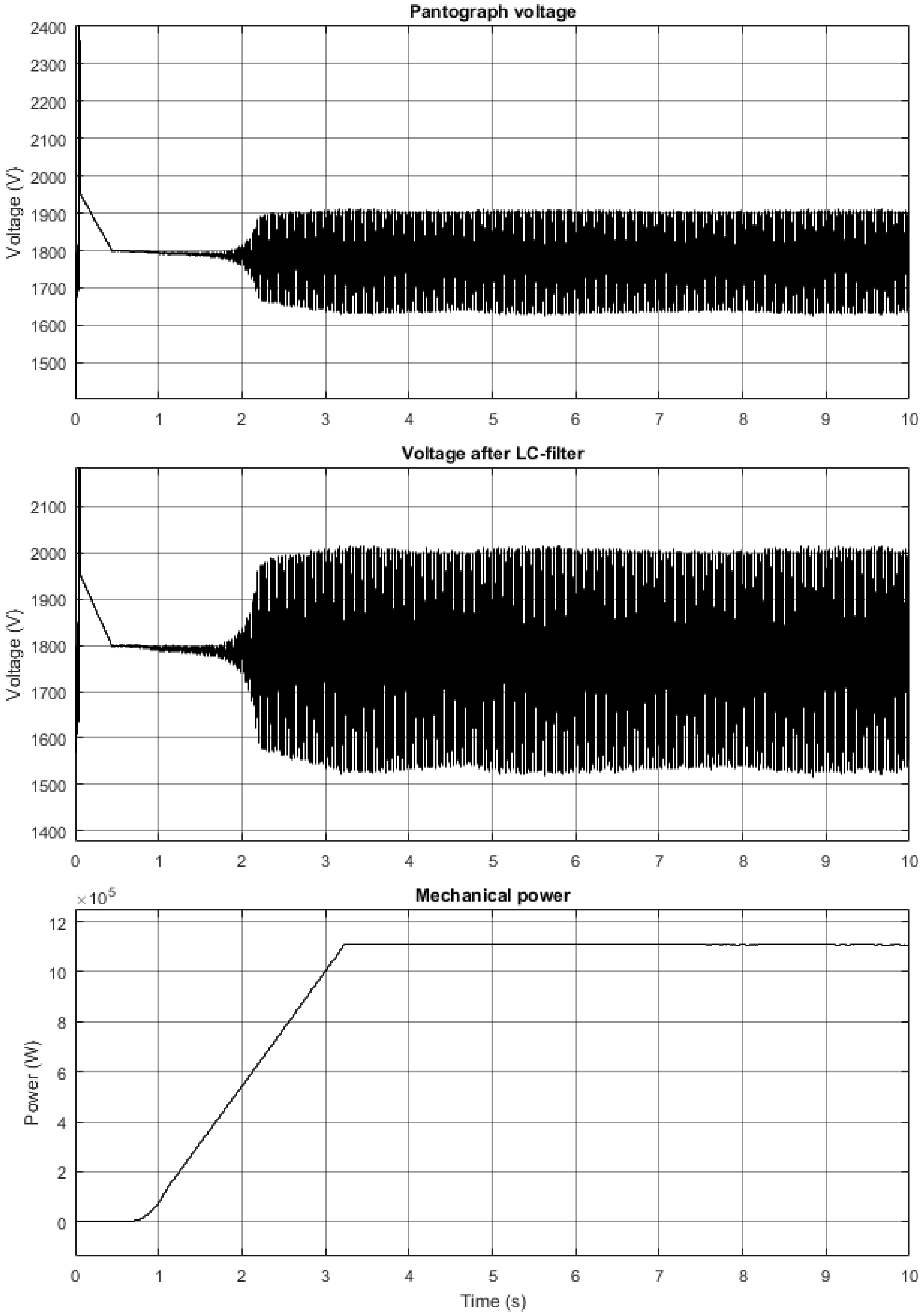

Figure 6-6: Voltage and power graph of the general train system with $L_{LC} = 1mH$

6-1-5 Simulation 4: Standard model with a large distance

Now the distance from substation to train is changed from $0.5km$ to $10.0km$. Because both the inductance in the overhead line and rail are far greater now, the system is expected to be less stable then in a situation with a low distance.

The following parameters have been used:

Table 6-9: Parameters for simulation with large distance

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $C = 10mF$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, **distance = 10 km**
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, **distance = 10 km**
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

The results of this system can be seen in the following table:

Table 6-10: Results of simulation 4 Large distance

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
4	Distance=10km	1500	700	1000	Yes	0.5 MW, 19%	unstable

When having a larger distance, the inductance and resistance in both the overhead line and rail will increase. The system in now more sensitive for instability as can be seen in figure 6-7. When calculating the maximum stable power with the formula in section 1-4-3, it can be found that at $P = 0.5MW$ the system becomes unstable. This can also be seen in the figure. Also note that the frequency is lower then in the standard simulation of figure 6-3. That is obviously because of the higher inductance in the rail and overhead line. The voltage ripple after the LC-filter is high, having a peak to peak value of $\approx 1000V$ and these oscillations also translate back into the pantograph voltage. The target amount of power of $P \approx 1.1MW$ is not even hit. In the power graph a large fluctuation due to the voltage instability can be seen and because the voltage after the LC-filter is sometimes relatively low the motors can not function as they should do. The power fluctuation is not according to the specified maximum 15%. So this standard system with large distance between substation and train is unstable. Now the question rises if the stability formula of maximum stable power can also be proved by putting the resistance or inductance in the overhead line and rail to zero.

Because of the high voltage fluctuations and ripple in the power output, this system only meets requirement 1. So it will be called ”unstable”.

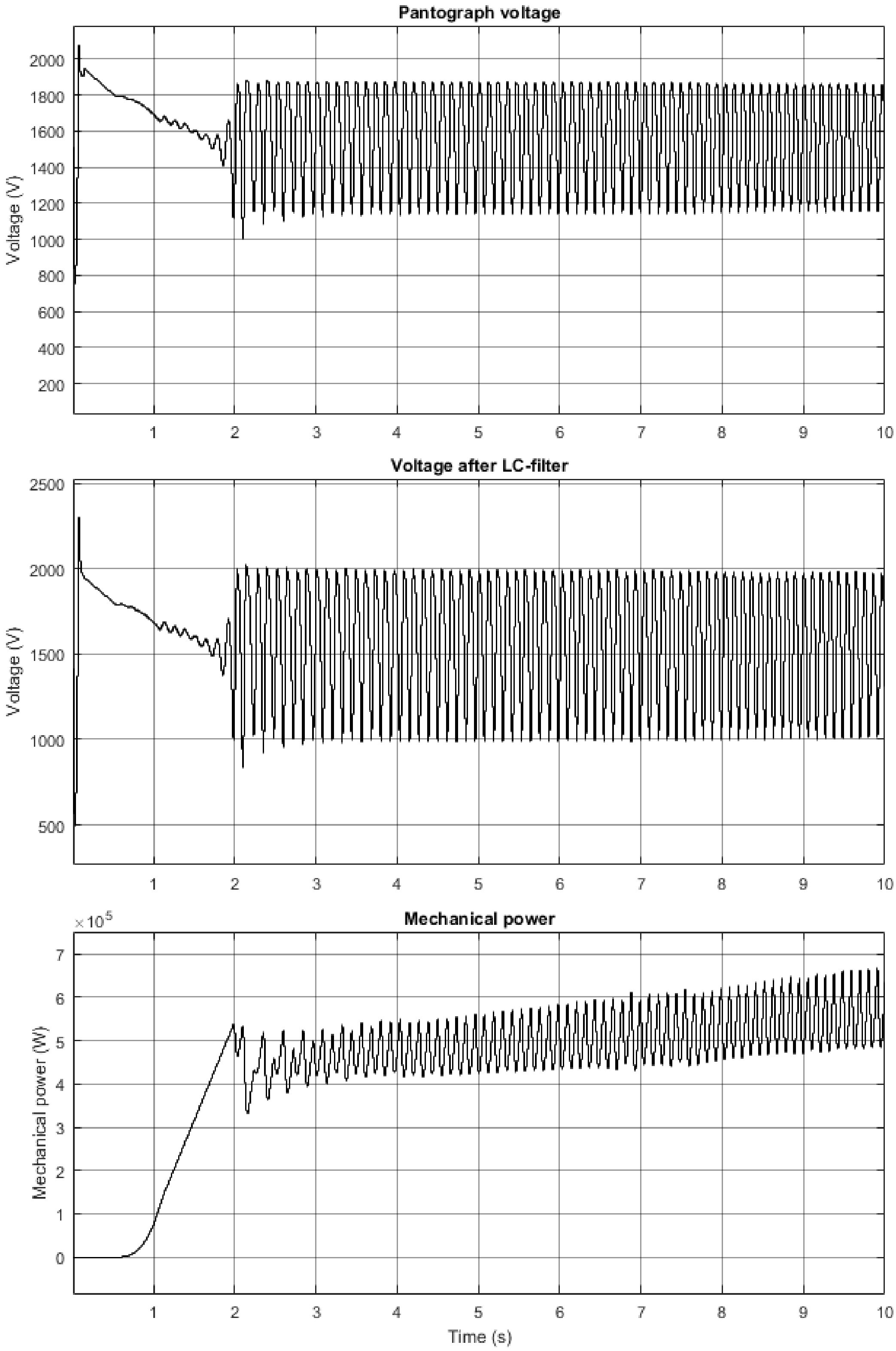

Figure 6-7: Voltage and power graph of the general train system with a $distance = 10km$

6-1-6 Simulation 5: Influence of overhead line and rail resistance

Now the same simulation with high distance from train to substation will be performed but now the overhead line and rail **resistance** set to zero in order to see if the instability is due to the resistance or inductance. The results can be seen in figure 6-8.

The following parameters have been used:

Table 6-11: Parameters for general train model simulation without auxiliary supply

Substation	1800 V DC source with series diode
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $C = 10mF$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $\boldsymbol{R = 0m\Omega/km}$, **distance = 10 km**
Rail track	$L = 0.7mH/km$, $\boldsymbol{R = 0m\Omega/km}$, **distance = 10 km**
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $T_{requested**} = 99kNm$

When having zero resistance but still inductance in the overhead line and rail, oscillations will still be present. The results can be found in the following table:

Table 6-12: Results of simulation 5 Large distance, overhead line and rail resistance zero

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
5	$R_{rails} = 0$ $R_{overheadline} = 0$	1800	700	850	Yes	1.1 MW, 9%	Power output stable

It can be see that the voltage oscillation after the LC-filter is a little bit lower now than it was in simulation 4. The power output of the motors is higher because the average voltage is also higher. This is obviously caused by the less voltage drop on the resistance of the overhead line and rail because the resistance is zero. These small improvements makes the system from being ”unstable” to ”Power output stable”. However when thinking about the formula for maximum stable power, the system should be immediately unstable because there is no resistance in the circuit. This can also be seen in the figure because at the time where the motors start to take power from the grid (first the capacitor needs to be discharged to 1800 V), the oscillation starts. The system does meet requirement 1 and 3 but still not requirement 2. So it will be called ”Power output stable”.

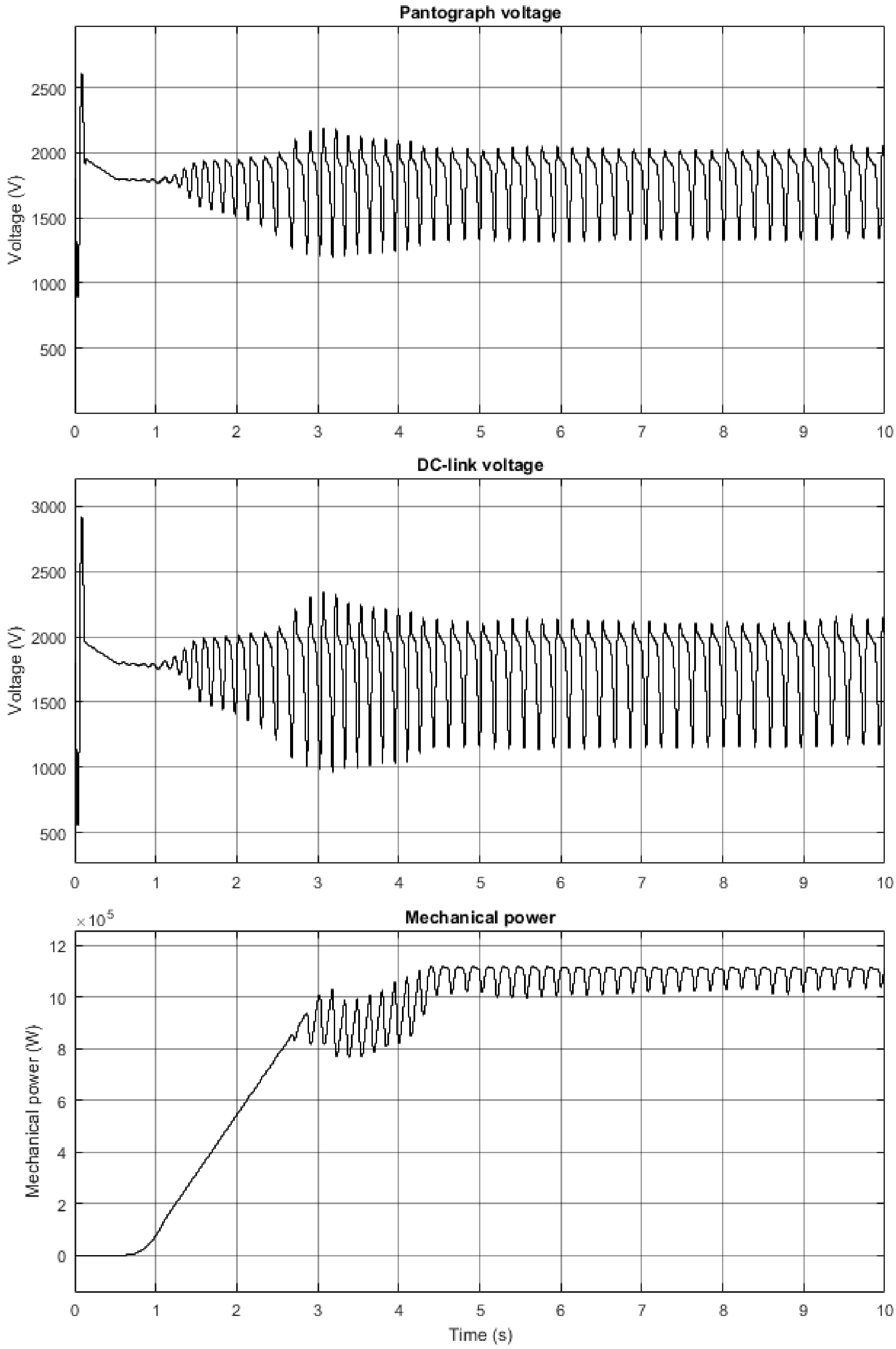

Figure 6-8: Voltage and power graph of the general train system with a $distance = 10km$, overhead line and rail resistance zero

6-1-7 Simulation 6: Influence of overhead line and rail inductance

Now the same simulation with high distance from train to substation will be performed but now the overhead line and rail **inductance** set to zero in order to see if the instability is due to the resistance or inductance. The results can be seen in figure 6-9.

The following parameters have been used:

Table 6-13: Parameters for general train model simulation, overhead line and rail inductance zero

Substation	1800 V DC source with series diode
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $C = 10mF$ and $L = 10mH$
Overhead line	$\boldsymbol{L = 0mH/km}$, $R = 40m\Omega/km$, **distance = 10 km**
Rail track	$\boldsymbol{L = 0mH/km}$, $R = 17.6m\Omega/km$, **distance = 10 km**
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $T_{requested**} = 99kNm$

When having only resistance in the overhead line and rail, the system is far more stable than in a state where there is any inductance, proving that inductance has a negative influence on the stability of the system. However when we look at the voltage after the LC-filter it is clear that the resistance is large enough to have the voltage dropped to a point where the requested torque of the system is limited in order to meet voltage regulations. Also note that the formula for maximum amount of stable power is giving a point of $1.8MW$. So this system should stay stable also according to the formula.

The results can be seen in the following table:

Table 6-14: Results of simulation 6 Large distance, overhead line and rail inductance zero

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
6	$L_{rails} = 0$ $L_{overheadline} = 0$	1300	0	0	Yes	9.25 MW, <1%	stable

Because the resistance has such damping effect on the oscillations in the system there is no oscillation to detect. The only change that can be seen is in the mechanical power. But this is because of the system that limits the current due to the voltage on the overhead line. The system can be called "stable" in this simulation.

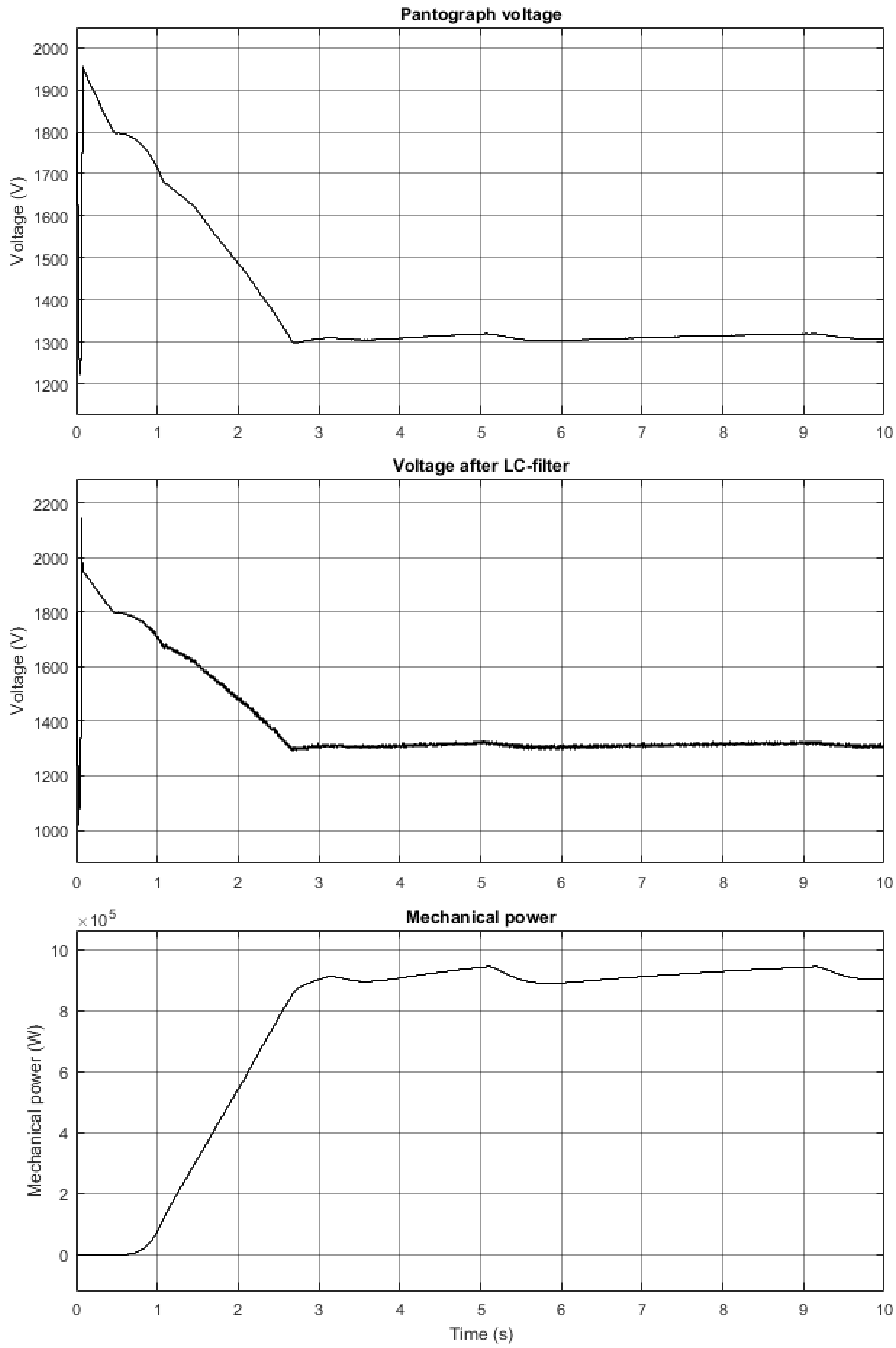

Figure 6-9: Voltage and power graph of the general train system with a $distance = 10km$, overhead line and rail inductance zero

6-1-8 Simulation 7: Influence of increasing the substation voltage with the original LC-filter

As already discussed earlier, increasing the voltage could be beneficial to the stability of the system. Not only less current needs to pass the filter but also more energy can be stored in the capacitance. In this simulation the voltage is doubled and the capacitance and inductance value are kept the same. As discussed before the voltage requirements are also doubled now. In figure 6-10 the simulation results can be seen.

The following parameters have been used:

Table 6-15: Parameters for general train model simulation with double voltage

Substation	**3600V DC source with series diode**
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $\boldsymbol{C = 10mF}$ **and** $\boldsymbol{L = 10mH}$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $T_{requested**} = 99kNm$

The results can be seen in the following graph:

Table 6-16: Results of simulation 7 doubled line voltage

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
7	3600V	3590	80	700	Yes	1.1 MW, <1%	Power output stable

Note that because of the same inductance and capacitance value as in the standard simulation, the system still has the same resonance frequency while the system is more stable now. This can also be shown with the formula for the maximum amount of stable power. The DC voltage appears there squared. So any voltage increase has a large effect on the stability of the system.

The voltage after the LC-filter is now just a little bit higher than the required 600 (=300*2) volts peak-peak. So it does not meet requirement 2. Requirement 1 and 3 are met because the voltage on the pantograph are within specs and the power does not show a ripple more then 15%. So this system is called ”Power output stable”.

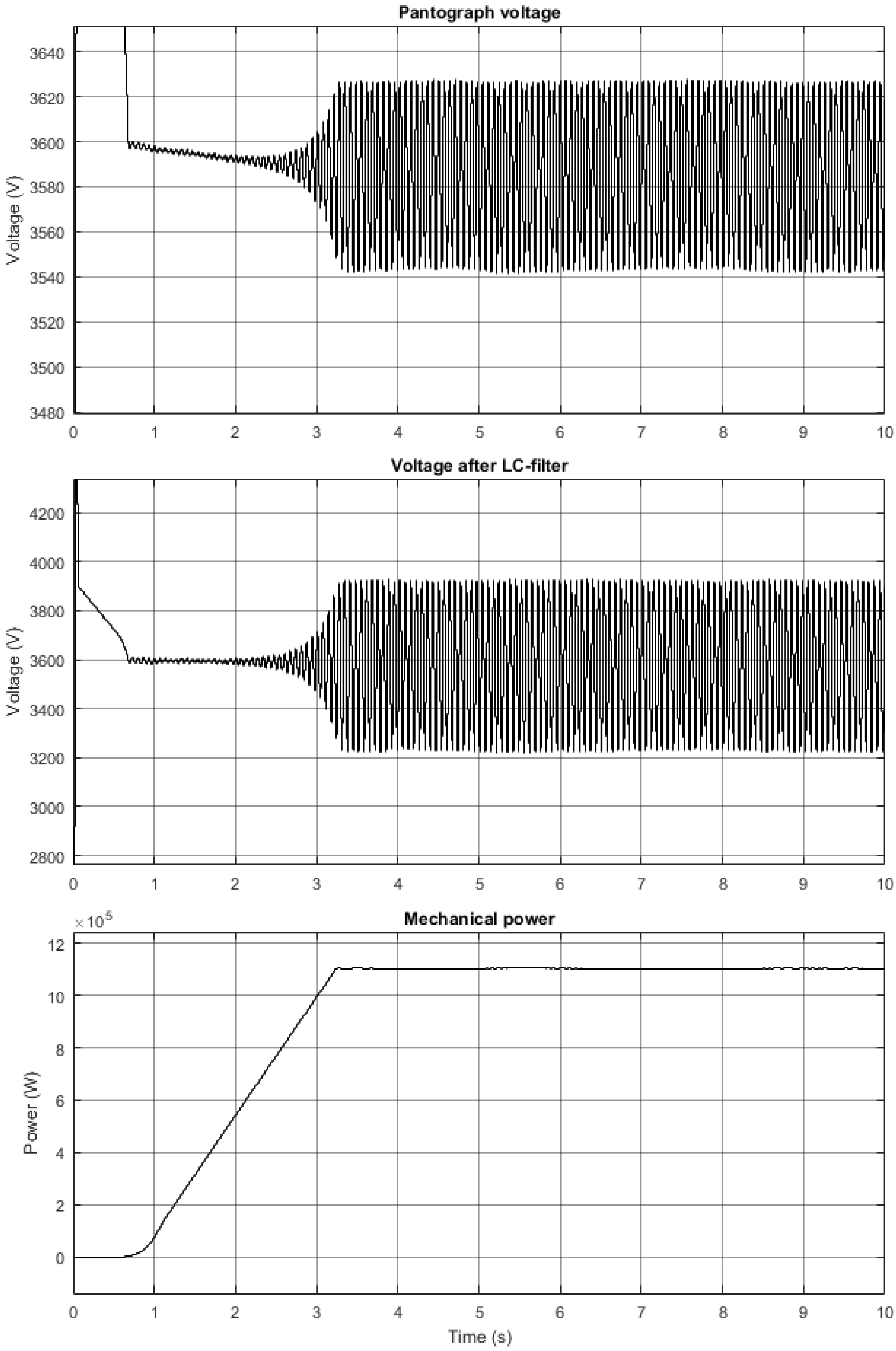

Figure 6-10: Voltage and power graph of the general train system with $V = 3.6kV$, $C = 10mF$ and $L = 10mH$

6-1-9 Simulation 8: Influence of increasing the substation voltage with the lower capacitance and higher inductance

In this simulation the voltage is doubled and the capacitance and inductance value are changed to give them the same energy storage capability as in the 1500 V network. Therefore the capacitance has been quartered and the inductance has been quadrupled in order to represent the same energy storage. This system has the same resonance frequency as the normal LC-filter.

The following parameters have been used:

Table 6-17: Parameters for general train model simulation with double voltage and new LC-filter

Substation	**3600V DC source with series diode**
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $\boldsymbol{C = 2.5mF}$ **and** $\boldsymbol{L = 40mH}$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $T_{requested**} = 99kNm$

The results can be seen in the following table:

Table 6-18: Results of simulation 8 doubled line voltage with changed inductance and capacitance

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
8	3600V $C = 2.5mF$ $L = 40mH$	3590	35	950	Yes	1.1 MW, <1%	Power output stable

Because the inductance is now 4 times bigger and the capacitance 4 times smaller than in simulation 7 a less stable is expected according to the maximum stable power formula. The voltage ripple is now higher than in the previous simulation with the normal inductance and capacitance. This system meets requirement 1 and 3 but still not requirement 2. So this system is also called ”Power output stable”.

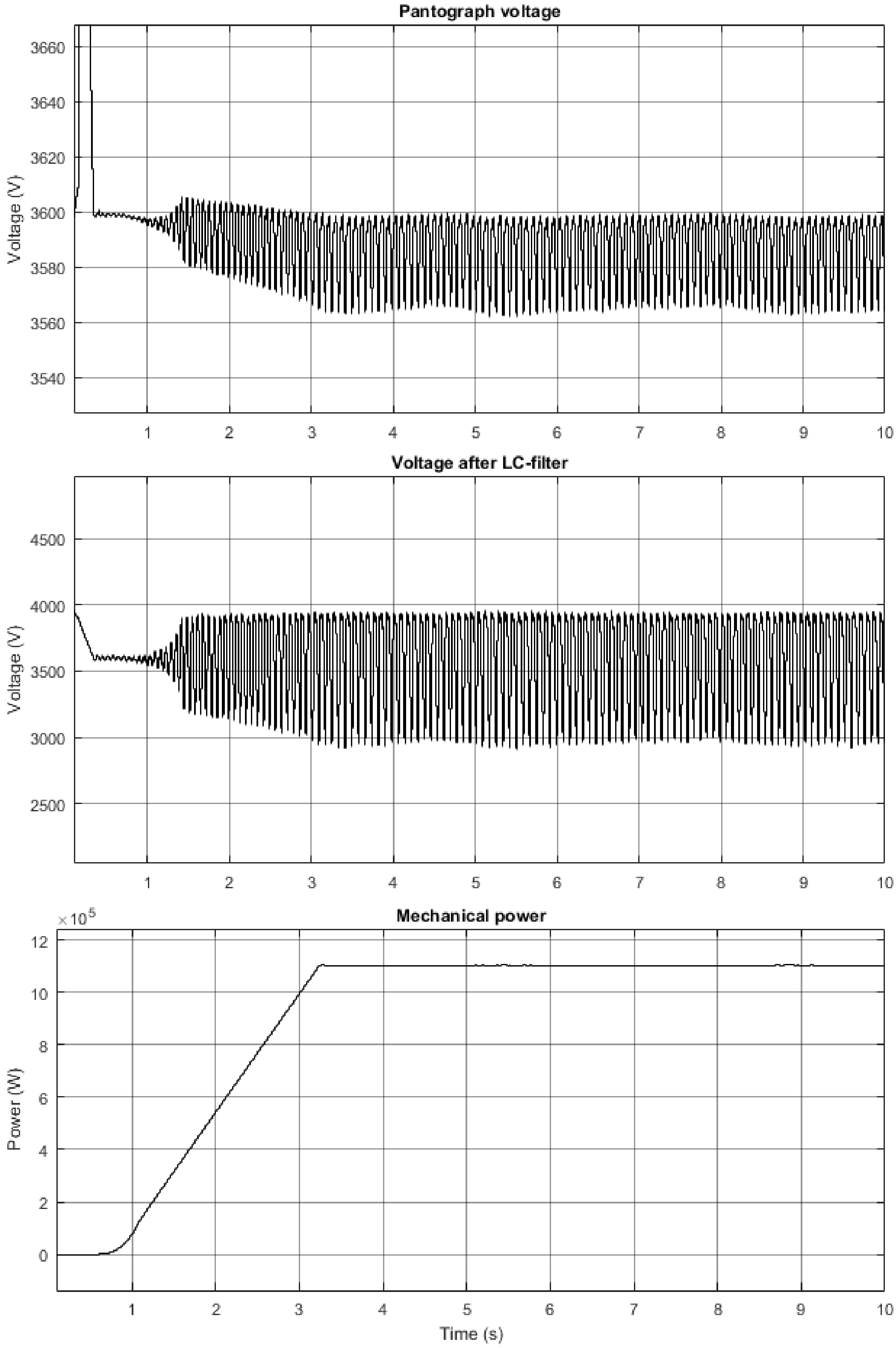

Figure 6-11: Voltage and power graph of the general train system with $V = 3.6kV$, $C = 2.5mF$ and $L = 40mH$

6-1-10 Simulation 9: Influence of second decelerating train

In this simulation two trains with with the parameters from simulation 0 have been simulated. One train decelerates from $34m/s$ with a torque setpoint of $-99kNm$ with a distance of $-0.5km$ from substation to train. The second train is accelerating with a torque setpoint of $99kNm$ with a distance of $0.5km$ from the substation. The torque, power, speed and acceleration of both trains (blue: train 1, red: train 2) can be seen in figure 6-12. The voltage and mechanical power graph can be found in figure 6-13.

The following parameters have been used:

Table 6-19: Parameters for general train model simulation with two trains

Substation	1800V DC source with series diode
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $C = 10mF$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, **distance = ±0.5 km**
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, **distance = ±0.5 km**
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $\boldsymbol{T_{requested**} = \pm 99kNm}$
V_{start}	**Train 1: $\boldsymbol{34m/s}$** after t=1.5 seconds, **Train 2: $\boldsymbol{0m/s}$**

It can be seen that the train that is putting energy back into the overhead line (blue), is far more stable then the accelerating train (red) is. The most unstable train will be used in the following table:

Table 6-20: Results of the two train simulation

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
9	Two trains	1800	60	650	Yes	1.16 MW <1%	Power output stable

It can be seen that the two train model is not very different from simulation 0, the standard model. Therefore it will also be called "Power output stable" because it does not satisfy requirement 2.

The two train construction does not have a significant better or worse stability then the standard model. Therefore it can be concluded that having a second train decelerating close to the first train, does not influence stability of the accelerating train.

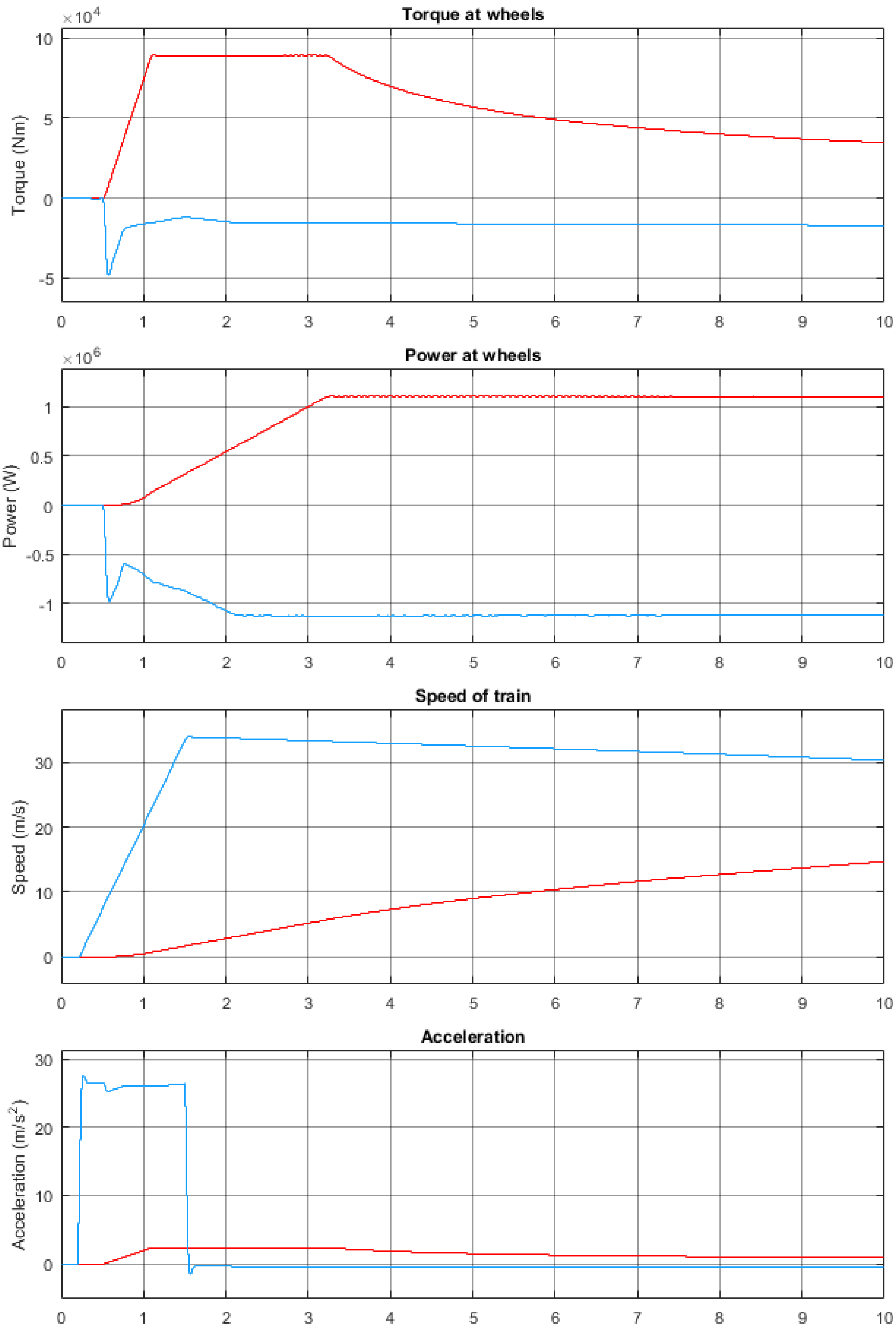

Figure 6-12: Torque at the wheels, power at the wheels, train speed and acceleration for the two train simulation. Blue: Recuperating train, Red: Accelerating train

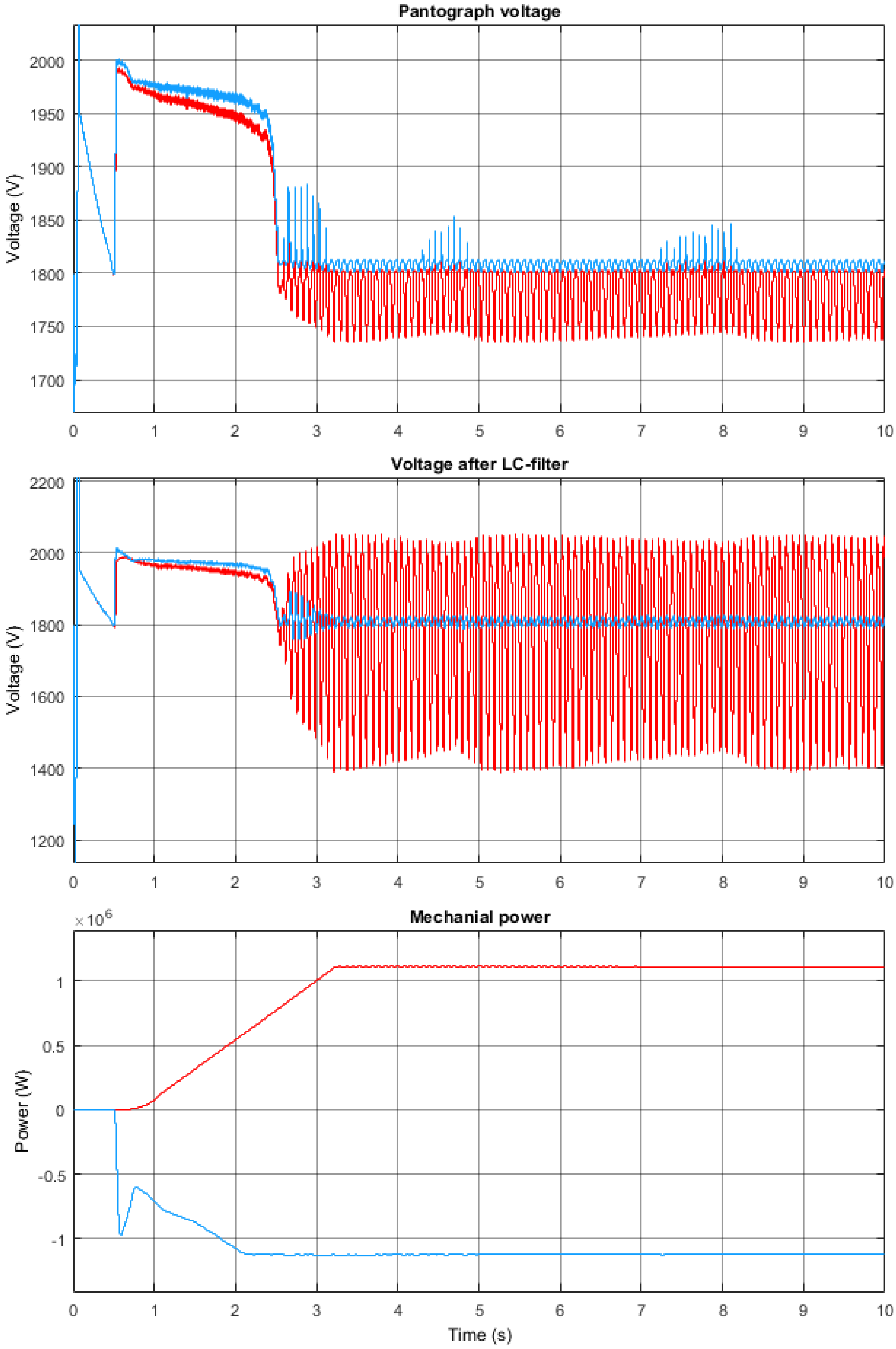

Figure 6-13: Voltage and power graph of the general train system with two trains

6-1-11 Simulation 10: RC damping branch

In this simulation a RC damping branch has been added after the LC-filter, as can be seen in figure 6-14. This damping branch has a value of 1.5Ω and $7mF$, while the capacitor of the LC-filter is only $3mF$. Making a total capacitance of $10mF$.

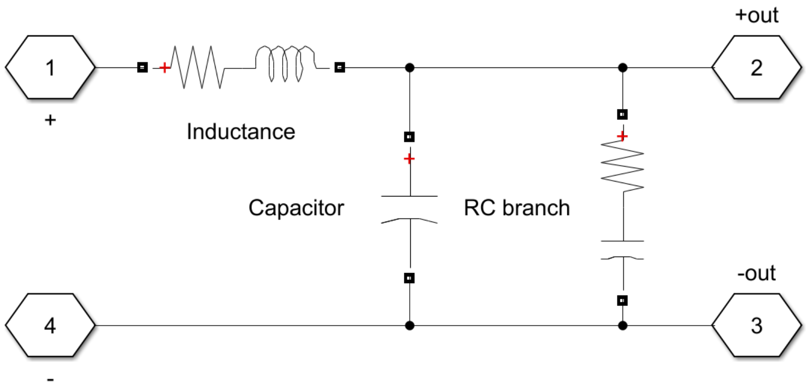

Figure 6-14: New LC-filter model with added RC branch

The results from this simulation can be found in figure 6-16. The following parameters have been used:

Table 6-21: Parameters for general train model simulation with RC damping branch

Substation	1800 V DC source with series diode
Motors	4 motors connected to 1 control unit as used in chapter validation
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter. $C = 3mF$ and $L = 10mH$
Damping branch	RC damping branch, $C = 7mF$ and $R = 1.5\Omega$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
Torque	At t=0.3s: $T_{requested**} = 99kNm$

Table 6-22: Results of the simulation with RC damping branch

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
11	Damping branch	1750	10	80	Yes	1.16 MW <1%	Stable

When comparing the results from this simulation with the results from the simulation 0, one can see that using a resistance in series with the capacitance, can increase the stability of the system significantly. The system is now stable with only $10mF$ total capacitance and constant power control. The question that raises now is: is it possible to make the capacitance smaller while keeping the system stable? There should be some formula to calculate with resistance capacitance pair delivers the most stable system. This has not been researched further within this thesis. Note that due to the variable line and rail inductance, finding the optimum parameters for the branch will be an optimisation, not a perfect solution.

One might think that, because the oscillation power which is dissipated now, a lot of power is dissipated in the resistance. When looking at figure 6-15, it can be seen that the power dissipation is not as high as one might think it would be. A maximum of 600 Watt is dissipated in the resistance. Which is not so high since more then $1.2MW$ of power is delivered to the motors. 600 W is also relatively easy to cool, so no problems have to be expected.

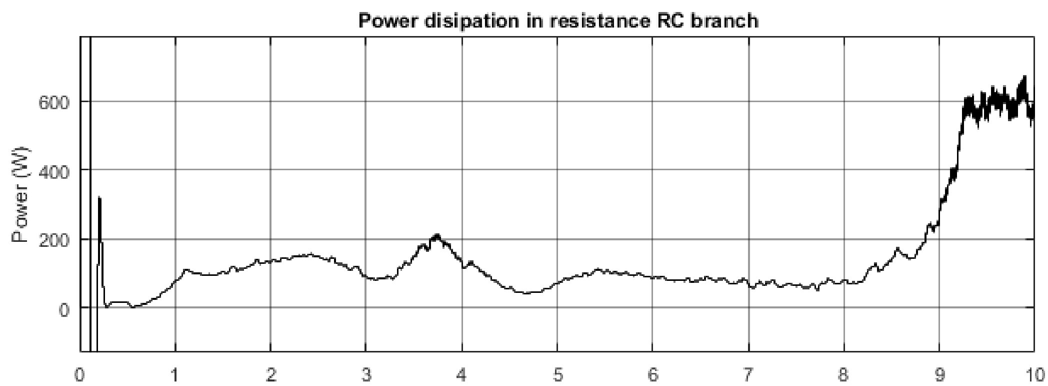

Figure 6-15: Power dissipation in the RC branch

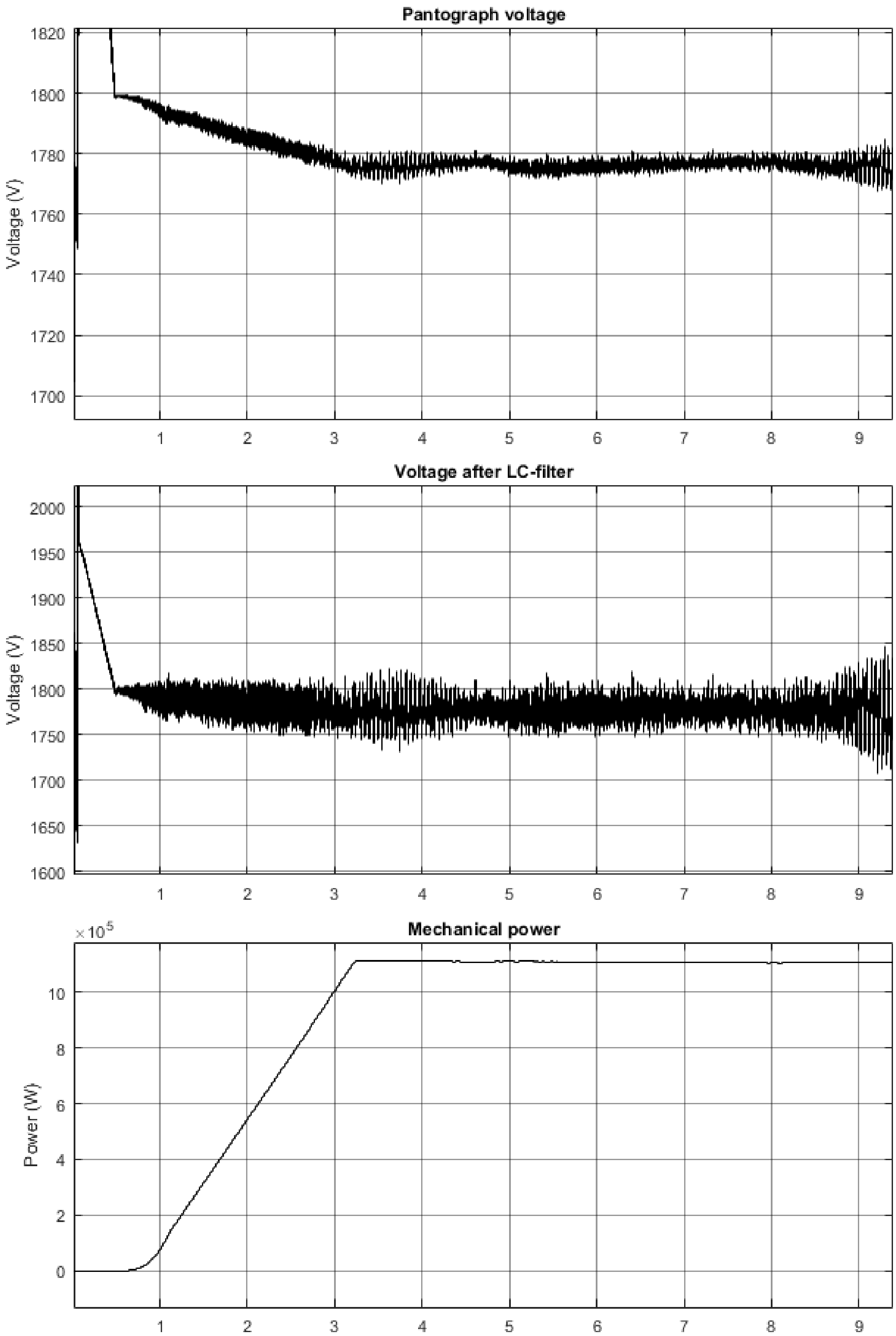

Figure 6-16: Voltage and power graph of the general train system with damping branch $10mF$

6-2 Conclusion of the first approach

These parameters have been the standard for the simulations in this chapter:

Table 6-23: Parameters for general train model simulation

Substation	1800 V DC voltage source with diode
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $C = 10mF$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Activated, $V_{start} = 1950V$, $V_{stop} = 1900V$, $R = 4\Omega$
motors	4 motors connected to 1 control unit as used in chapter validation
Torque	At t=0.3s: $T_{requisted} = 99kNm$

A summary of the results of all the simulations can be found below:

Table 6-24: Results of the first approach system

Sim. num.	Changes	$V_{pantograph}$ nominal (V)	$V_{pantograph}$ oscillation (V)	$V_{after-LC}$ oscillation (V)	Meet Req 1	Power output (P_{nom}, $ripple\%$)	Stable/Unstable
0	Standard	1760	75	700	Yes	1.11 MW, <1%	Power output stable
1	$C = 100mF$	1770	60	400	Yes	1.11 MW, <1%	Power output stable
2	$C = 1mF$	1750	100	900	Yes	6.5 MW, 8%	Power output stable
3	$L = 1mH$	1775	250	450	Yes	1.11 MW, <1%	Power output stable
4	Distance=10km	1500	700	1000	Yes	0.5 MW, 19%	unstable
5	$R_{rails} = 0$ $R_{overheadline} = 0$	1800	700	850	Yes	1.1 MW, 9%	Power output stable
6	$L_{rails} = 0$ $L_{overheadline} = 0$	1300	0	0	Yes	9.25 MW, <1%	stable
7	3600V	3590	80	700	Yes	1.1 MW, <1%	Power output stable
8	3600V $C = 2.5mF$ $L = 40mH$	3590	35	950	Yes	1.1MW, <1%	Power output stable
9	Two trains	1800	60	650	Yes	1.16 MW <1%	Power output stable
10	Damping branch	1750	10	80	Yes	1.16 MW <1%	Stable

For a simulation to the first requirement it should get a ”yes” in the colom ”Meet Req 1”. To pass the second requirement the oscillation voltage at the pantograph and after the LC should be less then 300V (except for the high voltage system they have to have a ripple less then 600 V). To pass the third requirement the power ripple had to be less than 15%.

It had be seen that even the biggest capacitance in these simulations was not big enough to keep the system stable in normal situations. When remembering the formula which have been discussed earlier in section 1-4-3, $P < U^2 \cdot \frac{R \cdot C}{L}$, it can be seen that for an 1.2 MW system one would need a capacitance of $146mF$ when using an inductance of $10mH$ and a distance of 0.5 km. This capacitance and inductance combination will give a resonance frequency of around 3.9 Hz for a distance of 0.5 km. So it can be concluded that a constant power controlled load is not a practical regime for a train. However, the RC branch, which was added to the filter, significantly improved the stability of the system. To implement this RC branch correctly further research is needed.

6-3 Resonance frequency of the LC-filter

In some of the simulation the frequency of the oscillation is discussed. The formula for the frequency of the LC-filter is as follows:

$$f = \frac{1}{2 * \pi * \sqrt{L * C}} \tag{6-1}$$

When increasing the capacitance or the inductance the frequency will decrease. In the previous simulations each time the frequency of the oscillation have been measured. In the figures the resonance that can be seen is the resonance of the LC-filter, with some exceptions as explained in the text.

6-4 Possible changes to improve stability

Looking back to the results of this first approach the model can be changed to get a better stability performance. However these possible changes may change the working of the entire system.

6-4-1 Changing the control strategy for the voltage

Momentarily the voltage controlled current limiter, part of the power/torque limiter of the traction controller, is controlled by the pantograph voltage. This because it is used to meet the norm regarding the voltage and currents on the pantograph. However it has been seen in simulations that connecting the voltage sensing input of this block after the LC-filter has a positive effect on the system stability. When doing so the current limiter limits the current when voltage after the LC-filter goes below the threshold given in the norm. This is a far more active technique than using the pantograph voltage. However this can also mean that the pantograph voltage/current relation as described in the norm is not complied. This, however, proves that making the constant power control less constant power and more current/voltage controlled indeed increases stability. The effect of changing the point of measurement can be seen in figure 6-17. This can be compared with the simulation with a small capacitance (simulation 2), figure 6-5. When comparing both figures it can be seen easily that the voltage drop on the system with the changed voltage measurement point is far less than in the original system, meaning a more stable system.

6-4-2 Constant power control

As already discussed earlier in this thesis the constant power control can make the system unstable. A control regime with less constant power control, a regime more like a constant current control, would not have the stability problems as this control has. It is expected that a lot of the problems regarding stability can be solved by changing control regime, as will be shown in the next chapter where the same system is tested without any control regime.

6-4-3 Changing the feedback loop of the constant control system

The feedback loop can be changed in order to make the system more stable. When you make, for example, the feedback loop slower than the resonance time of the LC-filter, the constant power regime is not able to change the traction current fast enough to follow the change in voltage. This would make the system less constant power in times you can not use the constant power regime.

6-4-4 Implementing the R_{ESR} of the LC-filter capacitor

In the model of the LC-filter no ESR resistance of the capacitance is included (note that the inductance has an ESR implemented however unfortunately it has been set to zero resistance in the simulation in this chapter). The datasheet of a similar capacitance as used in the trains was found by a supplier [35]. This $4mF$, $1900V$ capacitance has a R_{ESR} of less than $0.5m\Omega$. This value is too low to have an influence on the damping of the system oscillation. A quick simulation has been performed which concluded that this small resistance does not play a role in the stability of the system.

6-4-5 RC shunt filter

Knowing that the filter has resonance problems, a RC shunt damping network could be added to dissipate the AC energy in the voltage after the LC-filter. This could improve the stability of the system as proven in simulation 11. Further investigation should be done to the value of the resistance and the capacitance of the RC branch in order to be able to make a more stable system with a smaller capacitance value. This technique has proven to be a promising way of increasing the stability in simulations.

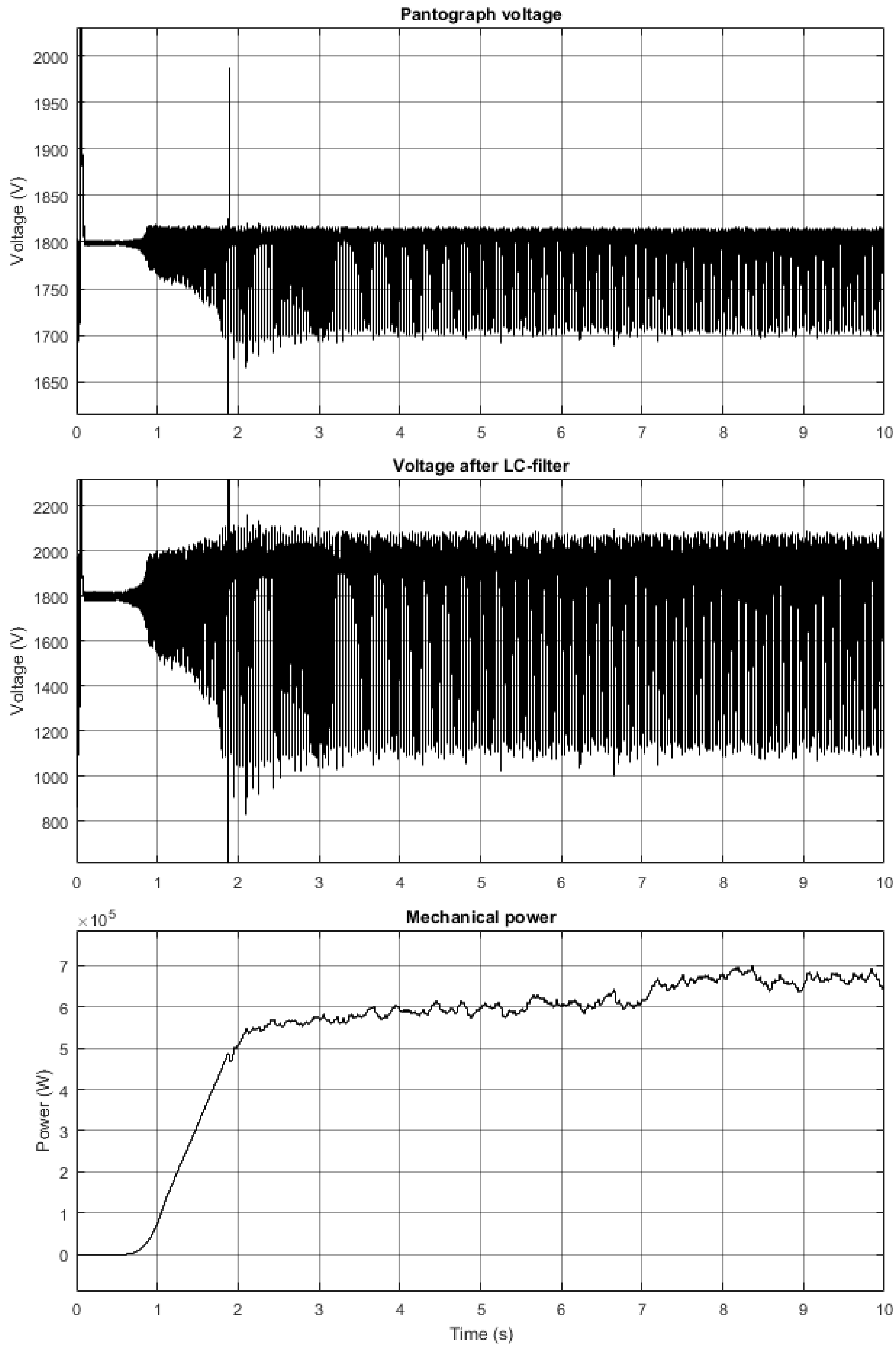

Figure 6-17: Voltage and power graph of the general train system with $C_{LC} = 1mF$, point of voltage measurement for the current limited changed

Chapter 7

Results second approach: No motor control regime

In the previous chapter about the results of simulation system 1 the conclusion has been drown that the capacitance of the LC-filter has to be very large, or has to be damped with a RC network, in order to let the constant power loaded system work in a stable way. Since the constant power control proved to be unstable in the first approach, a second approach has been made. In this approach all the voltage/power active controls are removed to investigate what a pure passive system does with the stability. For this reason a second simulation system has been constructed.

This model does change the frequency and the voltage on the motors, after a certain moment in time. So no constant power control is used. The inverter is now controlled by a PWM generator generating a 25 Hz signal on a 100 kHz (which is rather high for such high powers, but it is not expected to make such a great difference in results) carrier signal with a modulation index of 0.8.

The PWM generator with the inverter gives the motors a typical no load speed of around 80 rad/sec. The motors deliver their maximum rated power at 75 rad/sec for a 25 Hz stator frequency. The train is externally accelerated to that speed (while the motors are put on low voltage to keep them fluxed), and at $t = 0.4$ seconds the motors are put at full power. Because of this change in state a transient appears at $t{=}0.4$ seconds. The weight of the train is increased so that the speed stays almost constant in time, so that during the whole simulation cycle the maximum rated power is delivered to the wheels, making it easy to see what the motors do with the stability of the system. In the simulation the transient does not count in the requirements for stability. Therefore the requirements are applied after the transient. Normally around $t = 0.7$ seconds.

The model of the system can be seen in figure 7-1, and the model of the complete traction in figure 7-2. To have no active voltage or power controlled models in the system, the brake chopper and the auxiliary supply are not included in the system. The torque and power at wheels, train speed and acceleration can be seen in figure 7-3. Here it can be seen that the train is accelerated from zero to 75 rad/sec in the first 0.15 seconds. The speed of 75 rad/sec corresponds to a train speed of 8 m/s. At t = 0.4 the transients from the motors can be seen. Most of the transients are damped at t = 0.7 seconds. At that time the requirements will be tested.

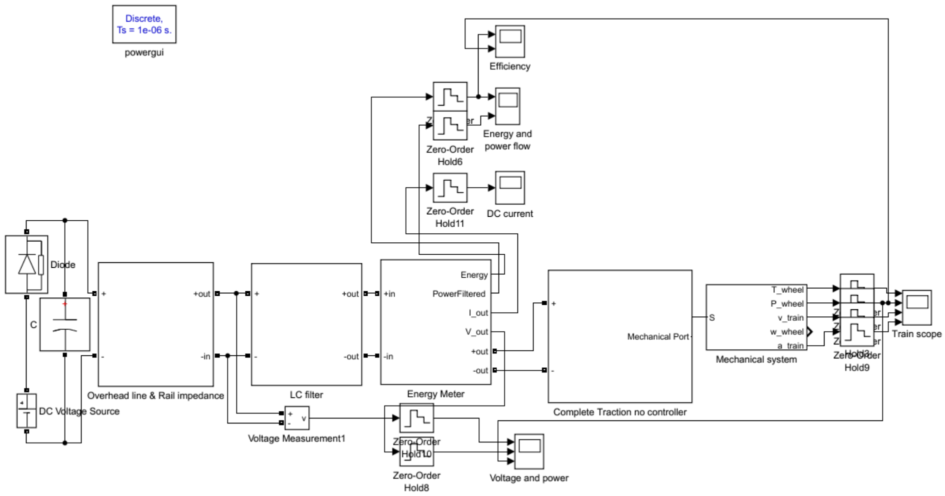

Figure 7-1: Second simulation model of the general train. Here no traction controller is used.

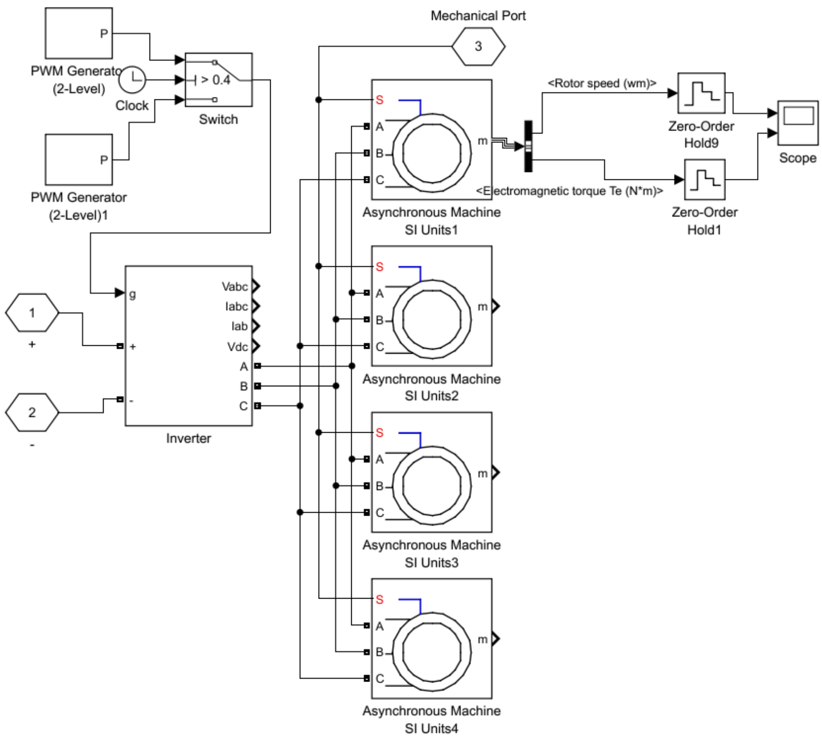

Figure 7-2: Model of the traction system of the second system

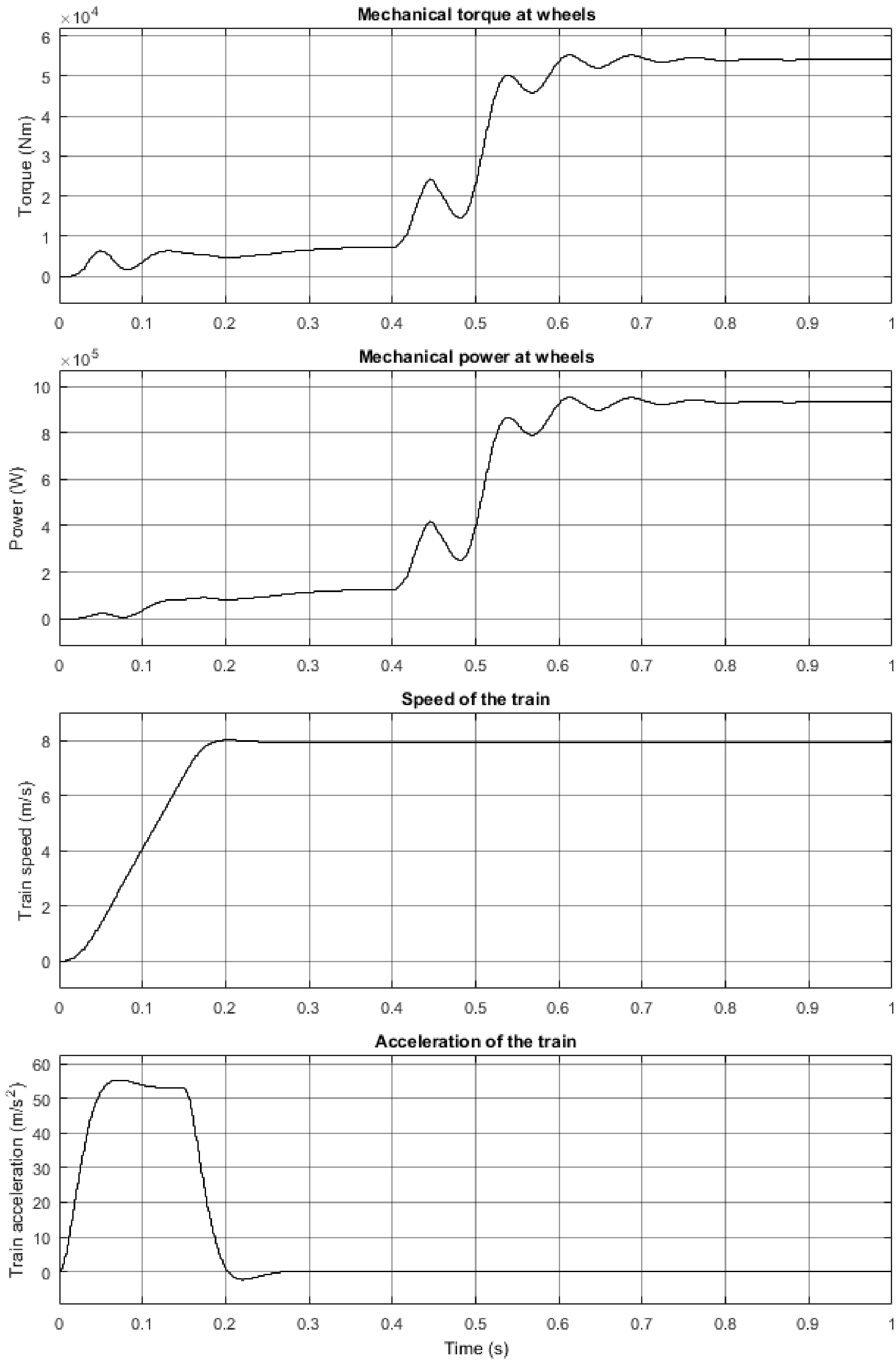

Figure 7-3: Torque, Power at wheels, speed and acceleration of the train. Cycle of the second approach

7-0-1 Simulation 2.0: Model with 10 mF without constant power control

The first simulation that is being done with the new model is called simulation 2.0. As already explained above there is no traction control in this system. The graph of this simulation can be found in figure 7-4.

The following parameters have been used.

Table 7-1: Parameters for general train model simulation, second approach, standard system

Substation	1800 V DC voltage source with diode and $C = 100\mu F$
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $\boldsymbol{C = 10mF}$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Not connected
motors	4 motors connected to 1 inverter
Control	100 kHz PWM generated with 25Hz, modulation: 0.8

As can be seen in figure 7-4 the voltage across the pantograph and across the LC-filter does meet both requirement 1 and 2. At t=0.4 seconds the inverter output voltage is set to a modulation index of 0.8. At this point the motor power starts to increase. The switching from a low voltage output of the inverter to a high output creates some transient in the system. The transient creates an AC voltage that has a frequency of around 10.6 Hz (measured at t=0.5). When calculating the frequency of the overhead line combined with the LC-filter with the values specified above, it can be calculated that the oscillation frequency of the input will be 14.9 Hz. So the AC frequency that can be seen in the voltage on figure 7-4 is not from the input filter and overhead line. Probably it is a combination of the inductances in the motor and the LC-filters capacitance.

Note that the system is highly damped and that the 10.6 Hz oscillation quickly disappears, making this system a very stable system.

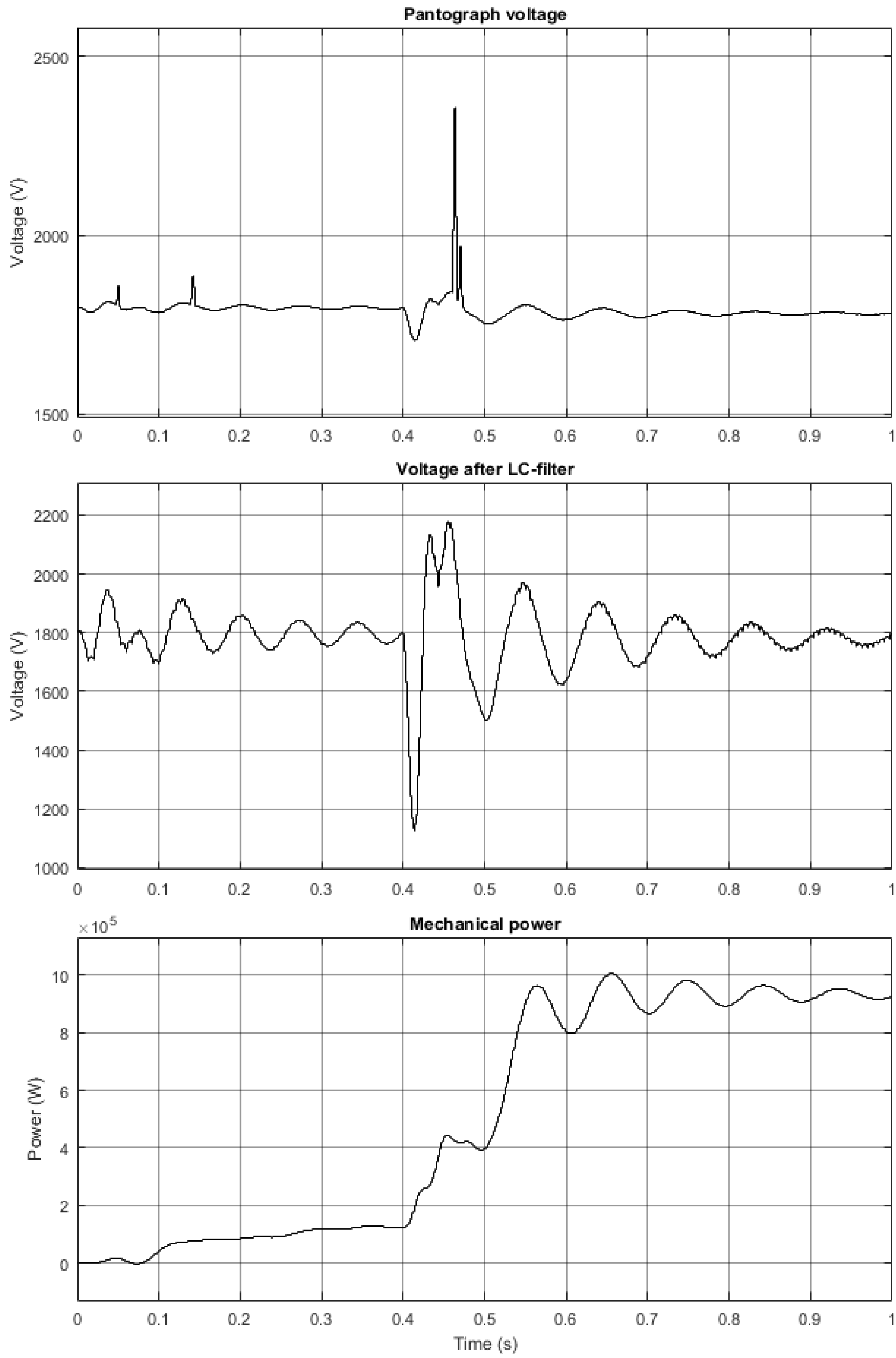

Figure 7-4: Voltage and power graph of the second approach with $C = 10mF$

7-0-2 Simulation 2.1: Model with smallest capacitance stable system

Multiple simulations have been done to find the lowest possible capacitance in which the system will remain stable. The results of this smallest capacitance stable system can be seen in figure 7-5.

The following parameters have been used:

Table 7-2: Parameters for general train model simulation, second approach, smallest capacitance system

Substation	1800 V DC voltage source with diode and $C = 100\mu F$
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $\boldsymbol{C = 0.8mF}$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, distance = 0.5 km
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, distance = 0.5 km
Braking chopper	Not connected
motors	4 motors connected to 1 inverter
Control	100 kHz PWM generated with 25Hz, modulation: 0.8

In the figure it can be seen that this system with a far smaller capacitance as used in the system with constant power control, is still stable. The oscillation that is present in the voltage of the LC-filter is just within the maximum voltage ripple specified in requirement 2. Requirement 1 is met, the voltage on the pantograph after t = 0.7s is according specifications. Requirement 3 is also met because the mechanical power ripple is small enough to pass this requirement. So this system have passed all test, making this system a ”stable” system.

A spectrum analyser has been placed at the voltage after the LC-filter. The oscillations that can be seen in the voltage after the LC-filter from t=0.7 to t = 1 seconds have a frequency of 150, 300 and 450 Hz. These are the 6th, 12th and 18th harmonic of the frequency of the inverter, which are caused by the switching of the inverter. The 10.6 Hz harmonic that has been found in the first simulation now changed into a 13.46 Hz harmonic. That proves that the frequency of that harmonic is dependent on the value of the capacitance.

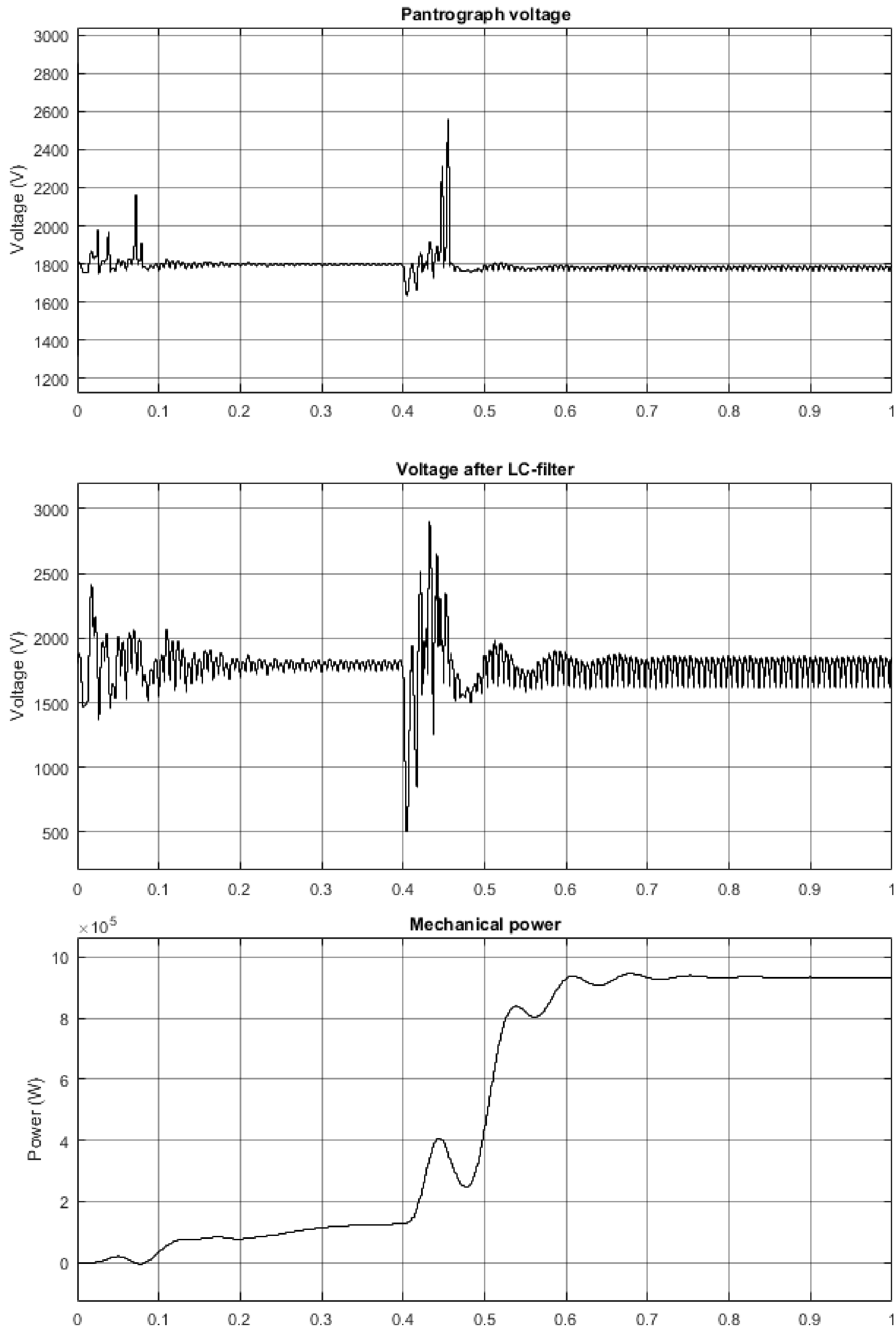

Figure 7-5: Voltage and power graph of the second approach with $C = 0.8mF$

7-0-3 Simulation 2.2: Model with smallest C stable system at large distance

When simulating the same system as simulation 2.1 with the small capacitance at a distance of 10 kilometer, it can be seen that this system is still stable at large distance. The results of this simulation can be found in figure 7-6. Note: smaller voltage step increase between t = 0.4 seconds and t = 0.7 seconds have been used in this simulation. So the transient is shifted in time and amplitude.

The following parameters have been used:

Table 7-3: Parameters for general train model simulation, second approach, smallest capacitance system

Substation	1800 V DC voltage source with diode and $C = 100\mu F$
Auxiliary supply	Not connected
LC-filter	Simple LC, second order filter, $\boldsymbol{C = 0.8mF}$ and $L = 10mH$
Overhead line	$L = 2.0mH/km$, $R = 40m\Omega/km$, **distance = 10 km**
Rail track	$L = 0.7mH/km$, $R = 17.6m\Omega/km$, **distance = 10 km**
Braking chopper	Not connected
motors	4 motors connected to 1 inverter
Control	100 kHz PWM generated with 25Hz, modulation: 0.8, from t = 0.6 seconds

After t = 0.6 seconds the system keeps to be stable as expected. Note that the output power of the machines is not as high as before because the voltage is too low to provide the power needed. This is obvious because of the larger resistance in the overhead line and rails. Next to the multiples of the 6th harmonic of the inverter frequency also a 5.9 Hz harmonic is present. Proving that the harmonic, which has already described as dependent on the value of the capacitance, also depends on the value of the inductance, meaning that this harmonic is some combination inductance and capacitance of the overhead line, LC-filter and the motor.

This system passes all requirements. Therefore even at large distance from substation to train the $0.8mF$ capacitance train is still stable.

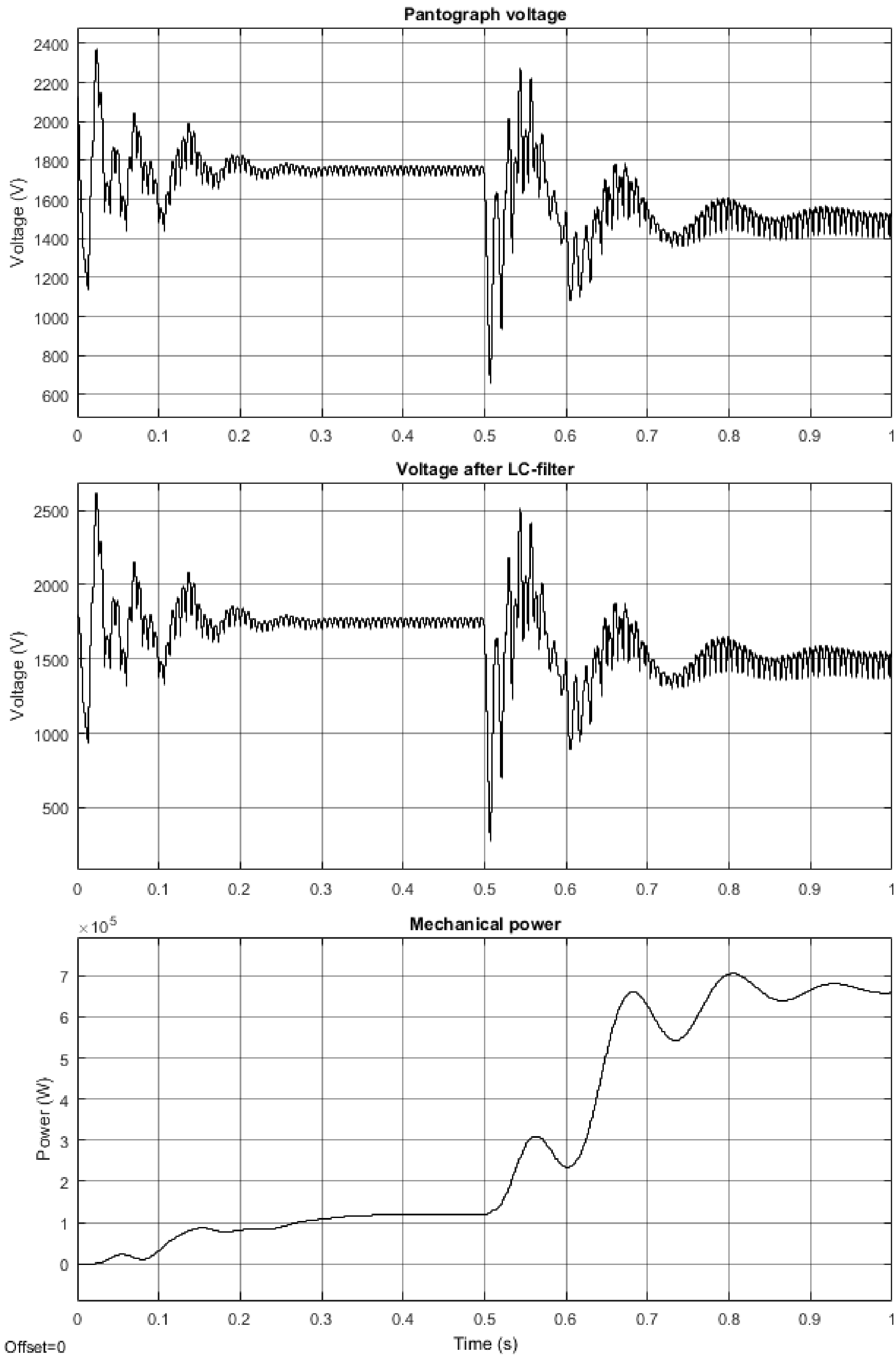

Figure 7-6: Voltage and power graph of the second approach with $C = 0.8mF$ with large distance

7-1 Conclusion of the second approach

Omitting the constant power control has a positive effect on the stability of the system. For a system with 1 MW of power the capacitance can be as low as $0.8mF$ while for a simple constant power controlled load (without damping branch), the capacitance should be around $140mF$, which is far higher.

When looking back to all the figures in this chapter, the question could be asked where the ripple in the voltage of the LC-filter comes from. Probably this is the resonance frequency of the combination of, a part of or translated, inductance of the motor and the capacitance of the LC-filter. Also the line impedance has an effect on the frequency of the harmonic. The amplitude of this oscillation and seems to vary with the size of the capacitance. However this does not seem to have a large negative effect on to the sizing of the LC-filter. The capacitance that has been found as smallest working capacitance for a stable system is $0.8mF$. When looking back to the train in chapter 4 validation, the DC-link capacitance was $3mF$ with a voltage of around the $2300V$. In that train far more energy is stored in the capacitance than the minimum needed energy storage that has been found during the simulations. Note that the motors used in this chapter are from that same train.

Chapter 8

Conclusion and Recommendations

8-1 Conclusion

In this thesis, a simulation model have been made of the Dutch DC railway system with a generalised train, in order to simulate the stability of the system.

Different simulations have been carried out, in order to examine the effect certain parameter variations have on the stability. Two systems have been considered, a constant power controlled system and a system where the motors had no controlling regime. An important factor is the value of the capacitance and inductance. A larger filter inductor results in an unstable system. Like wise, implementing a higher value capacitance will cause the system to be more stable.

Simulations have shown that a motor controller with a simple constant power control regime is unstable with normal values for the inductance and capacitance. However a damping branch can solve this problem up to an extent. A system without any controlling regime has proven to be more stable with smaller capacitance. When not using a control regime at all it is possible to have a stable system that can feed a total of 1 MW of motor-power with only a $0.8mF$ capacitance. With simple constant power control one would need an $140mF$ capacitance (when not using RC damping branch). With constant power control and a RC damping branch, $10mF$ of total capacitance will be sufficient. It can be concluded that a large part of the stability depends on the power control regime used. Also a 3 kV system has been investigated. It has been shown that due to the higher voltage the 3 kV system is more stable then the 1500 V network is.

8-2 Recommendations

During the research the following ideas, to obtain a stable system, came up and may need some further investigation.

8-2-1 Inverting substation

A research to an inverting substation with active power filtering has been done [17]. A inverter substation may have a positive effect on damping of an oscillation. The effectiveness on the stability of the system could be investigated.

8-2-2 Constant current control

The main cause of the oscillation is that the power intake of the machine is constant and not dependent on the voltage. Therefore it causes a higher current when voltage is dropping and thereby increasing the problem. If a constant current system is being used a far more stable system can be made.

8-2-3 RC branch

To have a damping branch in the LC filter, more research should be done for getting the best parameters for the resistance and the capacitance in this branch. It has already been found that the RC branch does have a positive effect on the stability of the system.

8-2-4 Varying the motor parameters

In chapter 7 it has been shown that the combination of the overhead line, LC-filter and motor parameters make a specific frequency that is not equal to the basic LC-filter and overhead line frequency. So it has been proven that the motor has some influence in the small oscillation that can be seen in figure 7-5. Further research could be done in determining the effect of the motor parameters on the stability of the system.

Appendix A

Resonance phenomena

In order to see what happens when a frequency of a voltage source meets the eigen-frequency of a LC filter, a simulation has been made. In figure A-1 one can see the a voltage source with a frequency of $159.2Hz$ and a LC filter with $L = 1mH$ and $C = 1mF$ with a resonance frequency of $159.2Hz$ which is the same as the voltage source. When simulating this system one can see the results in figure A-2. The voltage source has an amplitude of 1500V but it start to oscillate to much higher values in just a few 100 milliseconds. When there is not enough losses in the circuit, the circuit can quickly become unstable and destructive. This phenomena should be avoided at all times.

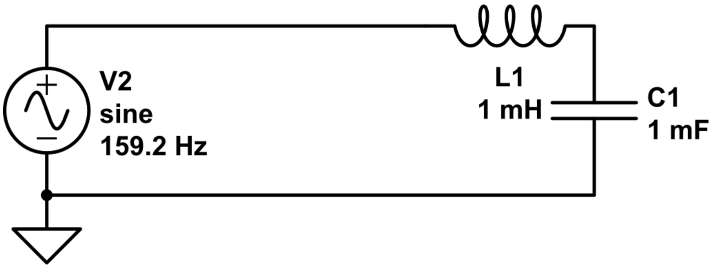

Figure A-1: Model for testing

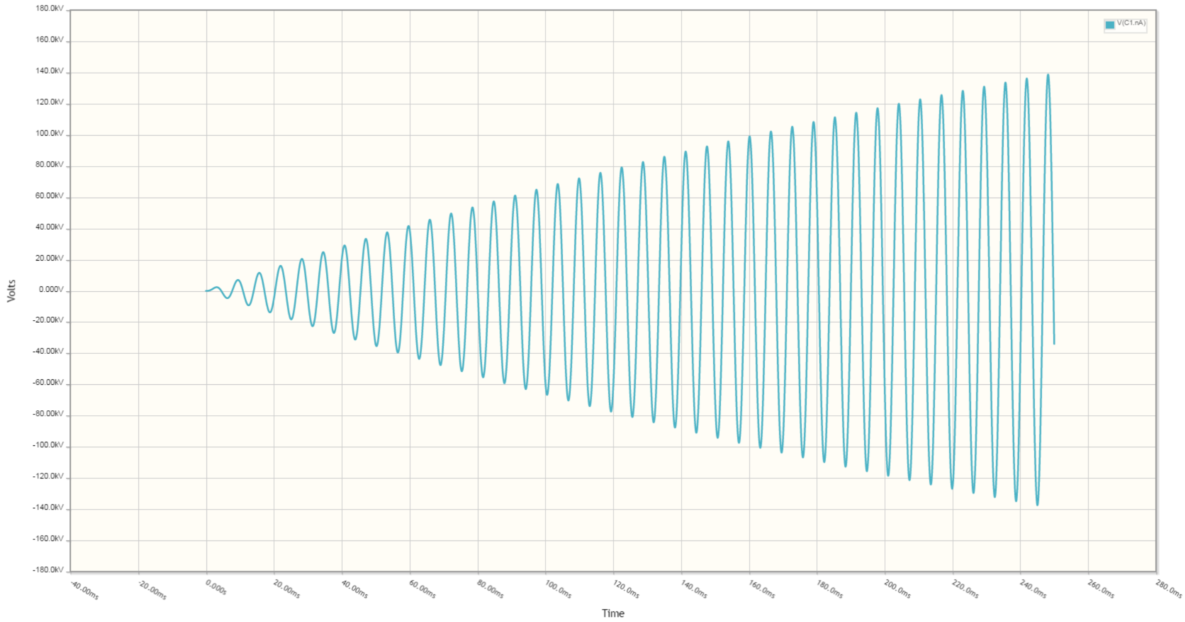

Figure A-2: Results from oscillating test model

When one would like to have a more realistic picture, where the source is not only a sinusoidal voltage source, one can look in figure A-3. Here a $1500V$ DC source is added in series with a $100V$ AC source at the same frequency as before. When one looks at the results in A-4 and see that there is not much changed now. The amplitude is still rising very steep and the oscillation is still present.

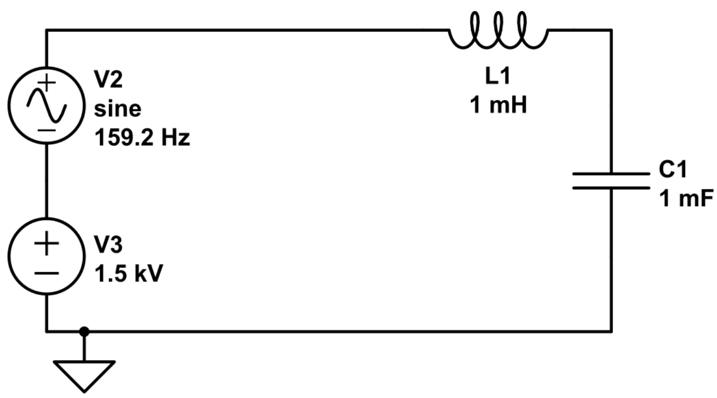

Figure A-3: Second model for testing

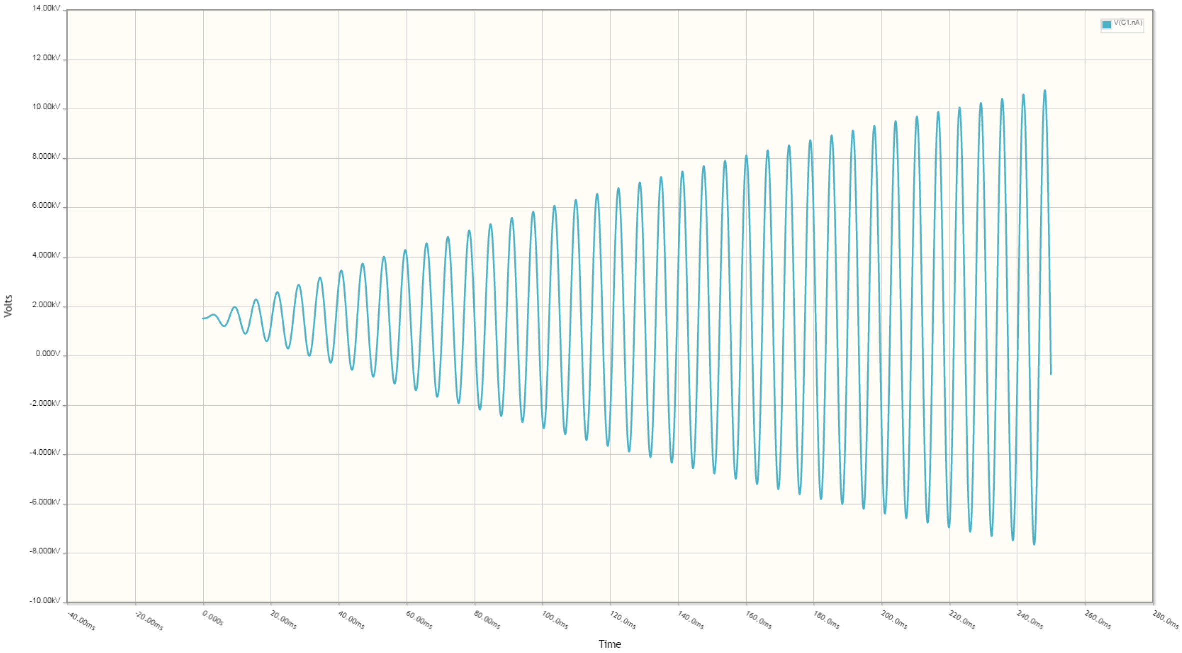

Figure A-4: Results from the second oscillating test model

Appendix B

The line capacitance

Calculations have been done in order to find the optimum parameters for the overhead line. These calculations have been done with Matlab Powergui Compute RLC line parameters tool. With this tool, one can fill in the line height and more parameters to calculate the R, L and C of the line. Three positive conductors have been used at 5.5 m, 5.5 m and 6 meter height from the ground. Both rails have been placed at 1mm distance from the ground with a x-axis displacement of 71.75 cm giving 1350 mm spacing between rails. Both rails are assumed solidly grounded (in reality they are not grounded) and were simulated as normal conductor wires. Because the system was already solidly grounded assumed it was not necessary to use extreme accurate parameters for the rails. Using a near DC frequency of 0.01 Hz one can get a resistance of $28.6m\Omega/km$, an inductance of $2.73mH/km$ and a capacitance of $1.22 \cdot 10^{-8}F/km$. It shows that the capacitance from overhead line to ground is very small.

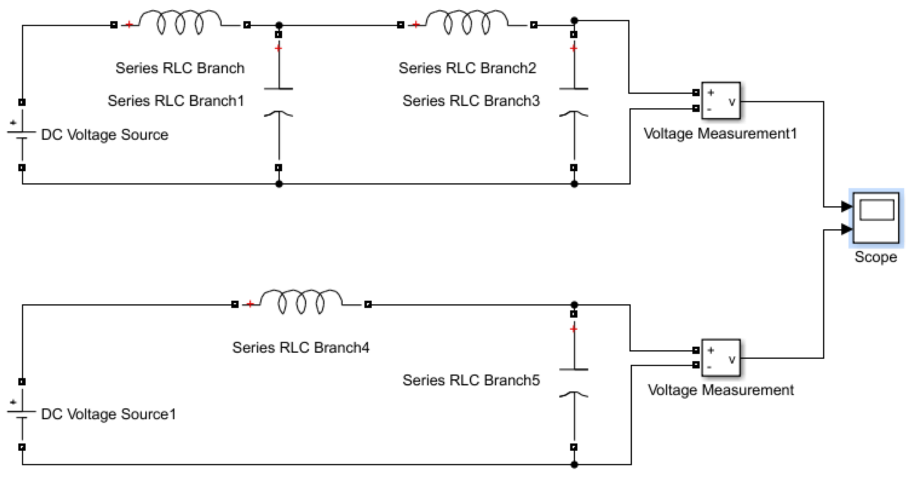

Figure B-1: Circuit to measure difference of neglecting or not the parasitic line capacitance with distance = 10km. Note that in the lower circuit inductance the inductance of both the LC filter as the line are in the same inductor

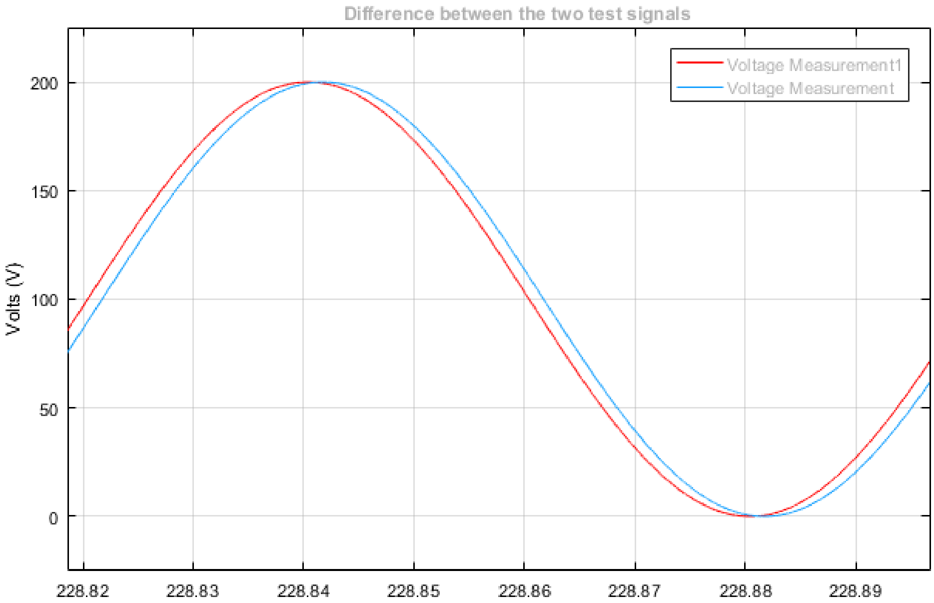

Figure B-2: The result after hundreds of cycles of the circuit of figure B-1

Appendix C

Spectrum analyser and aliasing

When one would like to view the different frequencies of a signal in a graph one would use the spectrum analyser option in Simulink. The sample frequency of the spectrum analyser is adaptable. The law of Nyquist says that the sample frequency should be at least twice the maximum frequency of the signal being sampled. With this in mind and looking back to the incoming signal one knows that filters should be used in order to avoid aliasing.However when filtering the signal, you will lose information and change the amplitude of higher frequencies close to the filter frequency. Simple research has been done to the optimum setting of the filter and sampling rate of the spectrum analyser. Problem with a too high sampling rate of the analyser is that the amount of calculations and memory usage increases when using smaller time steps. A too small time step gives lot of aliasing in the answer, which is of course not preferable. When setting the sample frequency to $20kHz$ a maximum of $10kHz$ can be observed in the spectrum analyser. Using two second order low pass filters with the $-3dB$ frequency at $5kHz$ a good result with only minor aliasing can be observed. Also the simulation time is very acceptable.

In figure C-1 one can see the test scheme. Voltage, here from a loaded 24 pulse rectifier system is being measured in a voltage measurement block. After this block 2 spectrum analysers are placed. The upper one has no filtering component, the lower one has 2 consecutive second order low pass filters with $f_{-3dB} = 5kHz$. The sampling rate of both the non-filtered as the filtered system is set to $20kHz$. In figure C-2 one can see the results from the non-filtered system. In figure C-3 one can see the filtered system. Note that the amount and the amplitude of false harmonics (peeks at non multiples of $1.20kHz$) is far higher in the non-filtered system as in the filtered system.

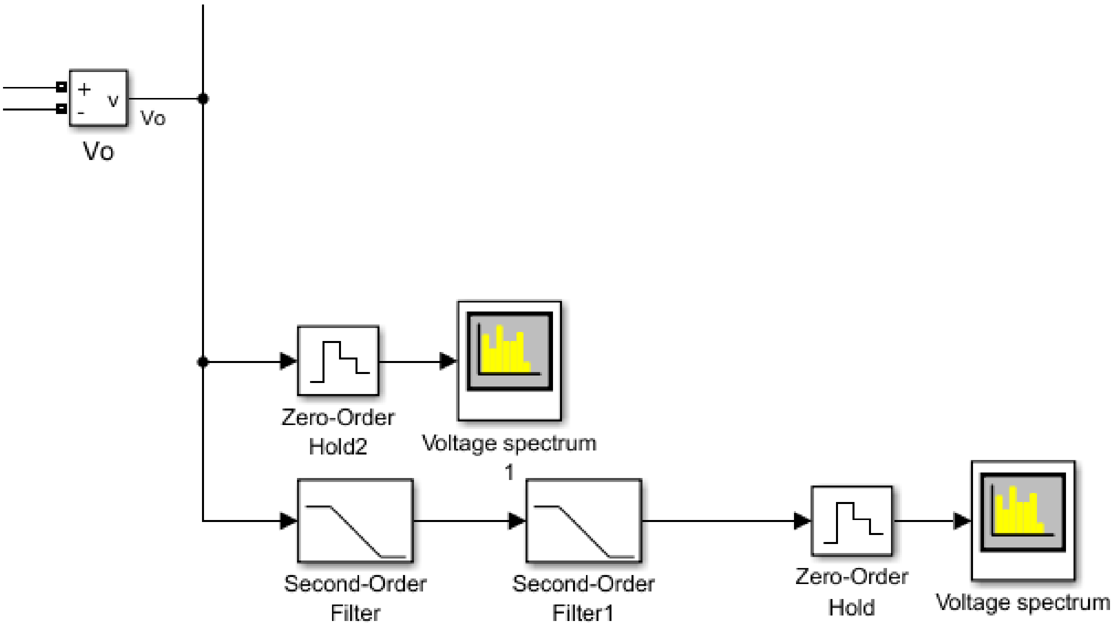

Figure C-1: Scheme made for comparing the differences between filtering and non-filtering

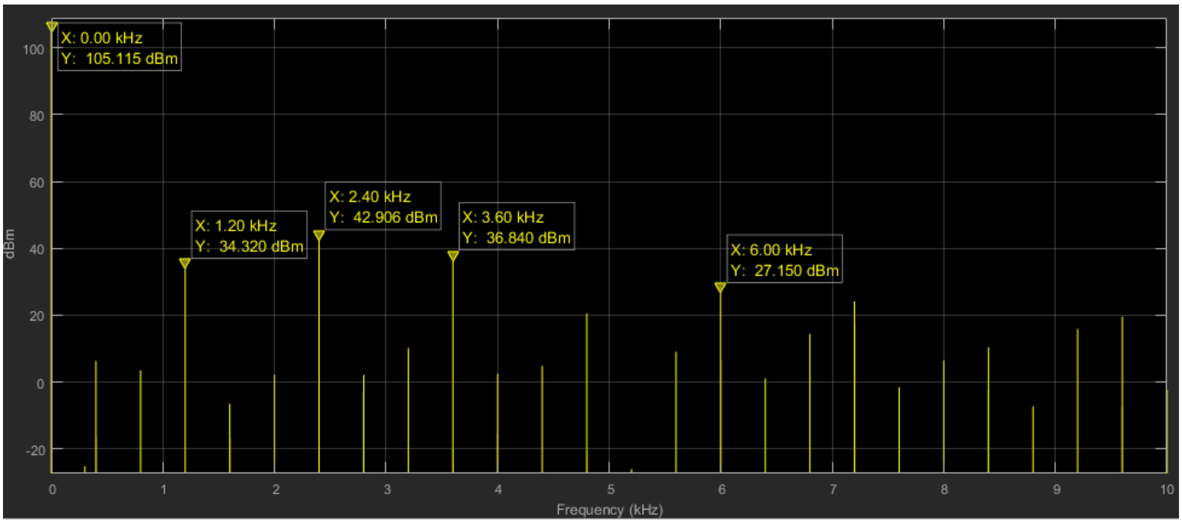

Figure C-2: Spectrum analyser result for non-filtered system

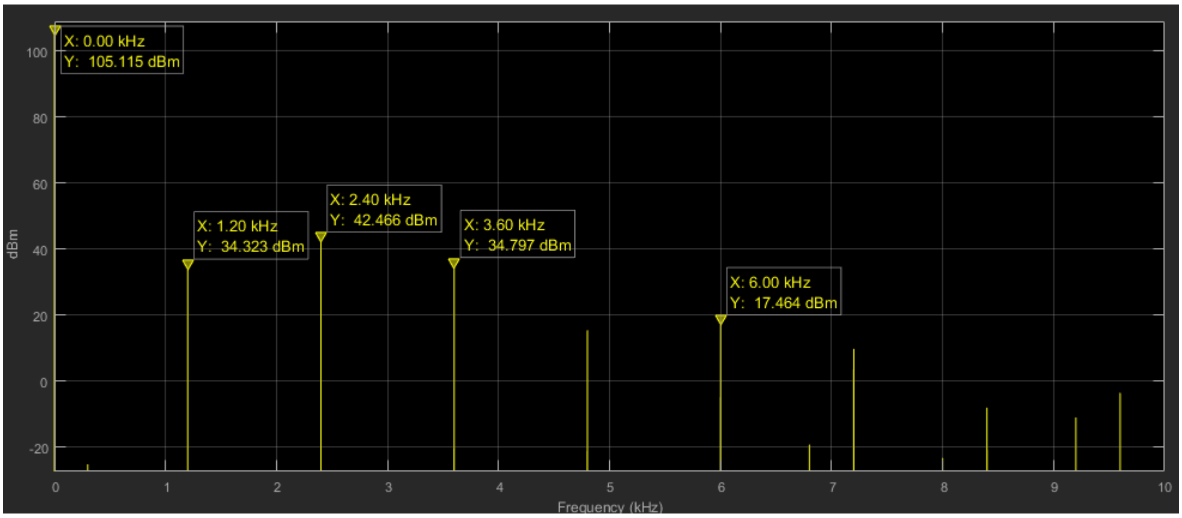

Figure C-3: Spectrum analyser result for filtered system

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