A Valley-Charging Power Approach for the Integration of In-Motion Charging Buses in DC Trolleygrids

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TUDelft

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by

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TU Delft

Preface

Studying bachelor in Electrical engineering, I discovered that there is an alternative approach to use energy. Renewable energy sources, energy efficiency or electric mobility. I had also dreamed about pursuing my Master degree abroad, living in a foreign country and learning about their culture. Once I found out about Sustainable Energy Technology, I knew this is the right path for me. I will forever remain grateful for studying this program at TU Delft, which changed me both professionally and personally.

Public transport can definitely play a vital role in the energy transition. The idea of In-Motion Charging (IMC) trolleybuses caught my eye immediately. Having used trolleybuses several times in my life and having the opportunity to work on making the familiar technology help towards sustainable urban environment were the decision makers.

I would like to thank Prof. dr. ir. Pavol Bauer and Dr. ir. Pedro Vergara Barrios for being present in the committee at my graduation. I would like to thank Dr. ir. Gautham Ram Chandra Mouli for being my supervisor, always finding time to discuss the thesis direction and providing valuable feedback on my steps. Very special thanks go to my daily supervisor, Ibrahim Diab. For his patience, as he was introducing me to the concept of modern trolley-grid and the new IMC technology. For his helpfulness, as he never refused a discussion about my work. He kept me on track and is one of the reasons I can present this Master thesis now. None of this would happen without my parents who made my stay in the Netherlands possible. I cannot have a better girlfriend than Martina, who supported me and was there for me all the time.

Marek Bistricky
Delft, August 15, 2022

Abstract

This Master thesis aims at studying the technology of In-Motion Charging (IMC) trolleybuses. These trolleybuses are equipped with an on-board battery large enough to provide energy for certain parts of the route. Thanks to that, the parts of the line do not have to be covered with overhead lines. As the vehicles charge their batteries en route, the IMC trolleybuses do not have to stop for depot charging which gives them advantage over regular e-buses.

Main task of this thesis is to develop and study a new charging scheme for IMC trolleybuses called the Valley-Charging. While conventional methods can only use two predefined charging powers, Valley-Charging allows changing the charging power over time based on the conditions on the trolley-grid. To evaluate the suitability to charge, methods of evaluating the state of the trolley-grid, such as traffic or power capacity of substations were developed into an estimator suggesting the appropriate charging power. The estimator is a set of conditions and constraints which use data that are available on-board of the trolleybus en route without any way of communication with other vehicles or infrastructure, such as bus voltage, bus current or bus position.

Multiple version of the estimator were developed and analysed for problematic circumstances. New conditions were added after that to make the estimator more complex. The Valley-Charging method supported by the estimator was implemented to 9 new IMC trolleybuses added to the Arnhem trolley-grid. Simulations with the latest version of the estimator showed that the new vehicles manage to service the line as it can collect enough energy under the overhead lines to successfully make the round trips. The results of the Valley-Charging scheme were compared with conventional charging schemes currently used. The Valley-Charging was found superior to the conventional methods in terms of energy collected or severity of technical limit violations.

Keywords: In-Motion Charging, trolleybus, trolley-grid, Valley-Charging, public transport, estimator, Arnhem

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Acronyms

A Arnhem Centraal. 29, 31, 58, 59, 71, 89, 98, 99, 102, 107, 112, 125

BMS Battery Management System. 5, 6

BPT Bus Public Transport. 9, 21

DoD Depth of Discharge. ix, 12, 13, 89

EoL End of Line. xxii, 128

EU European Union. 9

EV Electric Vehicle. viii, xvi, xix, 12, 132, 133, 177, 178

HVAC Heating, ventilation and air conditioning. xxi, 2, 27, 29, 31, 32, 57, 61, 69, 71, 72, 107, 108

IMC In-Motion Charging. v, vii–xix, xxi, xxii, 1–7, 9–15, 17–19, 21, 23–34, 38–41, 43–45, 47, 49, 52, 53, 57–59, 61, 69–73, 75, 78, 80, 82, 84–89, 91–93, 96–99, 101, 102, 104, 107–109, 111, 114, 116, 118, 120, 122–132, 135–139, 143, 145, 147, 149, 151, 155, 157, 159, 161, 163, 167, 169, 171, 173, 175, 177–180

LCO Lithium Cobalt Oxide. 12, 13

LFP Lithium Iron Phosphate. 12–14

Li-Ion Lithium-Ion. xxi, 4, 12–14

LMO Lithium Manganese Oxide. 12, 13

LTO Lithium Titanate Oxide. 12–15, 21

POV Point of View. 32, 33

SEI Solid Electrolytic Interface. 14

SoC State of Charge. ix, xi–xix, 5, 12, 14, 19, 23, 24, 27, 29–33, 69, 71–73, 75, 78, 80, 82, 84, 85, 89, 91, 92, 95, 96, 102, 104, 107–109, 111, 112, 114, 116, 118, 120, 122, 124–126, 129, 131, 133, 136, 143, 145, 147, 149, 151, 155, 157, 159, 161, 163, 167, 169, 171, 173, 175, 177, 178

SoE State of Energy. 14

W Wageningen. 31, 58, 71, 99

1
Introduction

The first chapter will provide introduction to the topic of this Master thesis, describe its background and state necessary information about the thesis. Section 1.1 briefly describes the trolleybus technology and then introduces the In-Motion Charging (IMC) technology. Also, the section explains the main concept of this thesis, the Valley-Charging approach. Following section 1.2 summarizes the basic information about the trolley-grid infrastructure. IMC projects are listed in section 1.3. The two sections 1.4 and 1.5 focus on describing the problem this thesis will try to solve and state the research questions. Last section 1.6 outlines the structure of this Master thesis.

1.1. Trolleybuses and Concept of In-Motion Charging (IMC)

The trolleybus technology was the first electrical mean of public transport introduced [36]. It uses electrical machine to propel the vehicle. An infrastructure called the trolley-grid is required to operate a trolleybus system as it provides the necessary power supply through current collectors.

Figure 1.1: Trolleybus connected to a trolley-grid via current collectors [2]

The power from the trolley-grid is used to not only propel the vehicles but also to power auxiliaries such as lighting, doors, ticket machines or even the Heating, ventilation and air conditioning (HVAC) system. Trolleybuses are also equipped by small diesel units or small batteries. They serve for cases of emergency when there is a failure of the trolley-grid or in cases of accident on the route when the trolleybus needs to change its route.

In the 90's, the trolleybuses were abandoned for regular fossil-fuel buses because of their lower operational costs, especially because they require no infrastructure [36]. Nowadays, as the demand for means of public transport to replace fossil-fuel vehicles is rising, the trolleybus using electricity is getting back into considerations of the municipalities all over the world. It is also because of the development of new trolleybus technologies that might make them superior even over electric buses. An example of such technology is the In-Motion Charging (IMC) trolleybus.

IMC trolleybus combines technologies of electric buses and trolleybuses. It is equipped by on-board battery which energy capacity is much larger than the one of regular trolleybus but also smaller than of an electric bus. Such vehicles use the current collectors to provide power to the electric motor and to charge the on-board battery at the same time while under the overhead lines. However, it can also operate in autonomous mode when the current collectors are disconnected from the overhead lines and the on-board battery is the only source of power and the IMC trolleybus behaves like an electric bus [16]. Thanks to this feature, the amount of overhead lines might be significantly reduced [16]. In IMC systems, only part of the route is covered by overhead lines where the IMC trolleybus charges its on-board battery while in-motion and the rest of the route is covered by using the battery power [5]. Conventional charging schemes used for IMC trolleybuses use only two charging powers, one for in-motion operation, Ψ, and one for standstill, Π.

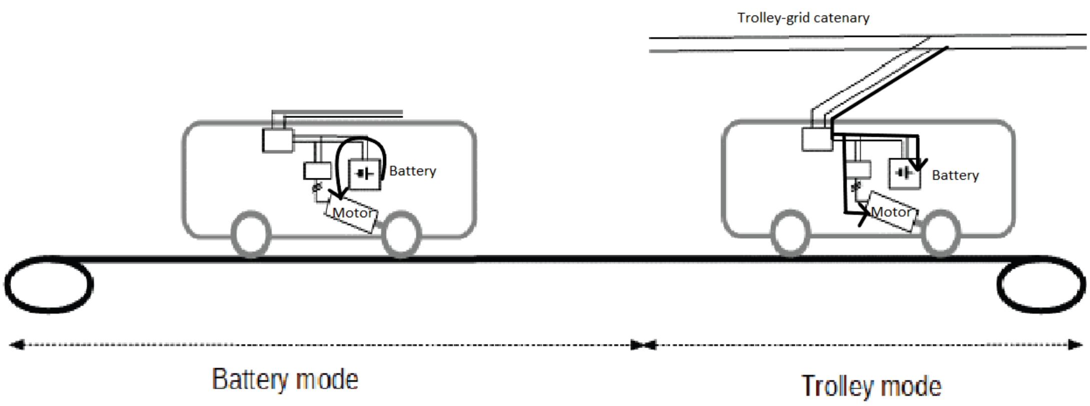


Figure 1.2: The idea of In-Motion Charging [2]

The biggest advantage over the electric bus is that the IMC trolleybus does not have to stop in depots for charging the battery but can do it while operating the public transport line [5, 16]. This not only brings reduction of the operation time as electric buses have to wait at the end of the line to partially recharge the battery but also reduction of the vehicle fleet. All IMC trolleybuses can be operating at the same time whereas some electric buses might be put aside to recharge. As the battery of IMC trolleybus does not have to provide energy for the whole route, it can be smaller than the one of the electric bus. This might bring significant reduction in battery mass and therefore improved efficiency of operation [16]. The only drawback of the IMC technology is the necessity of trolley-grid infrastructure, such as overhead lines, which the electric bus does not need.

Table 1.1: Advantages and disadvantages of regular trolleybus, IMC trolleybus and e-bus

	Regular Trolleybus		IMC Trolleybus		Electric Bus (e-bus)
+	Mature technology	+	Smaller battery (typically <100 [kWh])	+	No overhead lines needed
		+	Charging en route	+	Independent operation
		+	Smaller vehicle fleet		
-	Infrastructure	-	Infrastructure	-	Large battery (typically >250 [kWh])
-	No Flexibility			-	Depot Charging
				-	Large vehicle fleet

Unlike a regular trolleybus, the IMC trolleybus is much more flexible and can change its route easily as it can use the battery power in autonomous mode and go temporarily off-grid due to any kind of maintenance on the trolley-grid.

1.2. Trolley-grid

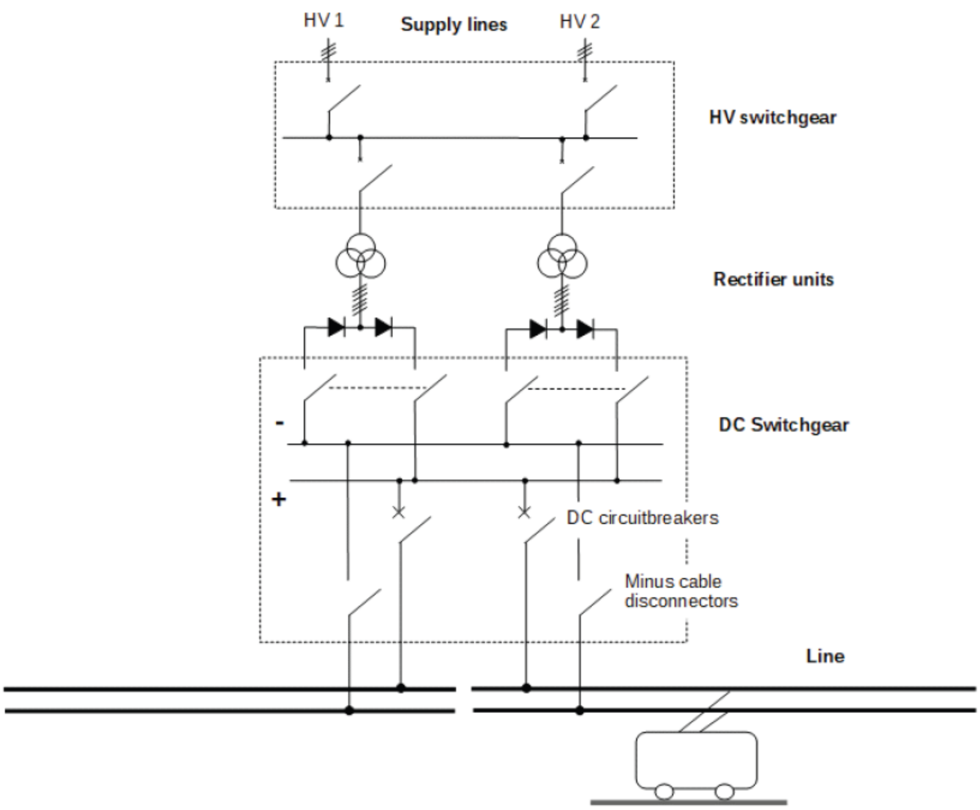


Figure 1.3: Electrical schematic of a typical trolley-grid substation [2]

Trolley-grid is a DC network used within municipalities to power trolleybuses from the overhead lines. The trolley-grid is supplied from the public distribution high-voltage AC grid. In a substation, there is a transformer which decreases the voltage first and then a rectifier that converts the power going from the AC grid into DC power suitable for trolley-grids [2]. Most of the substations are equipped by just the rectifier and no inverter which prevents from sending any recouped energy from the trolley-grid back to the public AC grid. This is a matter of power quality in the AC grid. A schematic of a typical substation supplying the trolley-grid might be seen in figure 1.3.

The trolley-grid is divided into supply sections which are all separately fed from the substations by the so called feeder cables. The substation can either supply just a single section or to provide power to multiple sections at the same time. Also, sections might be separated from each other meaning that the section can only be fed by one substation. Such section topology is called unilateral grid. When the sections are interconnected, they can use power supply in the most convenient way from other substations also, which is called bilateral connection. With the latter, the voltage drop is reduced and the transmission losses are lower. The length of the section can range from lower hundreds up to more than 1.5 [km].

The overhead lines consist of two parallel wires, one for a positive (higher) potential and one for negative (lower) potential [2]. The overhead line cables are characterized by their resistance, typically in order of $10^{-4}[\Omega/km]$. It is desirable to use low resistance cables as together with the amount of current going through it determines the amount of transmission losses. The resistance mentioned is per kilometer, which means the transmission losses increase with the distance from the substation. It is not desirable to maximize the area of the sections as it leads to higher losses. An effective way of reducing the total resistance of the electric path is to add another overhead line or extra feeder cable [2].

1.3. In-Motion Charging Projects

The IMC technology gave rise to organizations and focus groups that investigate on its feasibility within cities' public transport networks as well as raising awareness of this new mean of transport. They can play a vital role in convincing the responsible stakeholders about the need for sustainable urban mobility and thus making IMC more widespread.

A non-profit organization *Trolley:motion* deals with sustainable mobility in general. One of their main projects is the *trolley:2.0* which main field of interest is exactly the battery-assisted trolleybus. Established in 2018, they put together 9 partners of public transport operators, research organizations and industry companies, among which Technical University of Delft can be found. By research and simulations with real-operation inputs, they aim at proving the superiority of this technology over other vehicle types and emphasise its potential for smart grid utilization. Another project of *Trolley:motion* is called *Eliptic* which has been figuring out the drivers and barriers for integrating IMC vehicles into existing electrified public transport systems. They have also been comparing different means of transport from business perspective.

As the IMC technology has turned out to be promising and also thanks to the aforementioned organizations, some cities have already launched their pilot projects with battery trolleybuses to start utilizing the assets that IMC can bring such as less cabling in the city, reduction of stopping times, etc.

Table 1.2: In-Motion Charging Projects Typical Parameters. Ψ represents in-motion charging power, Π represents standstill charging power. On-grid/Off-grid ratio stands for part of route covered under the overhead lines/part of the route covered without the overhead lines

City	Battery Capacity	Ψ	Π	On-grid/Off-grid
Solingen, DE	45 kWh	240 kW	200 kW	23/77
Szeged, HU	80 kWh	130 kW	80 kW	44/56
Gdynia, PL	69 kWh	120 kW	90 kW	27/73
Eberswalde, DE	48 kWh	240 kW	90 kW	60/40
Prague, CZ	47 kWh	50 kW	N/A	10/90
Arnhem, NL	45 kWh	240 kW	200 kW	N/A
Landskrona, SWE	54 kWh	N/A	N/A	30/70

Table 1.2 shows examples of these pilot projects and their key parameters. All the projects make use of Li-Ion batteries, apart from Szeged where Nickel Metal Hydrid battery is still used. It is worth mentioning, that the towns of Solingen and Eberswalde are both using the same recent technology of

IMC500, which makes their in-motion charging power similar. Arnhem is also about to employ it. With regards to the *On-Grid/Off-grid* column, it refers to the fraction of route covered by overhead cables and the part that is being operated in battery mode. It can be seen that cover rate of 23% or 27% can be achieved. In Solingen, it is mainly due to the high charging power while in Gdynia with lower charging power, the battery capacity compensates for it. In Prague, the 10/90 rate can be misleading as the 10% route is a steep part of line where the aim is that the buses can exchange power in parallel operation. Other cities that also run the IMC system are for example Geneva, Zurich or St. Petersburg.

1.4. Problem Statement

It is desirable to keep up with the energy transition even in the transport sector and public transportation is a great way of doing so. They run on predefined lines, their distances may not be that high and they stick to a schedule which can be used to plan the service. Transforming diesel or other fossil fuel powered vehicles into a more sustainable electricity powered ones can have direct impact on better environment. By reducing the greenhouse gas emissions in the urban regions, the air quality can rapidly increase.

Let's assume that the diesel buses will be replaced for trolleybuses with IMC technology. One requirement arises from this decision and that the municipality needs to be equipped with a trolley-grid. If there is no such network, it means significant investments have to be made to build the infrastructure from scratch. There can be already existing tram or trolleybus network that can be used which is much more favourable option. However, such system might have been designed several years ago, may have already been extended by new lines since then and it might not be ready to accept such high-demanding new technology which IMC is.

Previous research [12, 11] has shown that adding a new IMC line to an already existing trolley-grid might cause issues in terms of substation power demand, voltage and current violations at some point. Violations refer to moments when the quantities exceed their allowed technical limit which might be harmful for the infrastructure. This mainly happens when the vehicles demand too high power supply at the same time. Nevertheless, this is not the case for every moment of the grid. Sometimes, the substation still has more power capacity left to be provided. With the emergence of new IMC technology called IMC500 allowing charging up to 240 [kW] and 500 [kW] vehicle input in total, the amount of charging power that can be fed to the vehicle has increased and this unused potential of the trolley-grid may be utilized. The problem is that as there already were violations with the basic charging power levels, the new IMC500 cannot charge high power constantly. They need to perform sort of peak shaving and shift their power demand to times when there is enough power available.

This thesis proposes a new charging scheme for IMC trolleybuses called the Valley-Charging. It can change its charging power over time based on the conditions of the trolley-grid. When the conditions are favorable it can even charge maximal power. When there are multiple buses connected, the vehicle can change the charging power accordingly so the power demand is within the substation limit. This way the Valley-Charging approach can help to both secure safe utilization of the trolley-grid and also help the newly added trolleybuses to be reliable in terms of their battery SoC.

1.5. Research Questions

Having stated the problem this thesis deals with, it will now be transformed into research questions that this thesis answers.

As it has been already mentioned, the Valley-Charging approach for IMC trolleybuses enables the vehicle to charge at times when there is enough power capacity available and such power demand does not break power, voltage and current limits. It means the Battery Management System (BMS) which is in charge of demanding the charging power needs to make a suitable decision corresponding with the current state of the trolley-grid in terms of the aforementioned parameters. However, the vehicles operating in the trolley-grid receive no information from the substations nor from the section level about the traffic density on the section where they currently are. In order to utilize the potential of the

Valley-Charging approach and the trolley-grid the most, a way of deciding when and how much power to draw needs to be developed. When the suggestion provided is not accurate enough it might not only make the IMC trolleybus inoperable as the total energy collected will not be enough to operate the autonomous part of the route but also on the other extreme side it might put the substation and section into jeopardy in terms of safety.

To provide the information of what power the IMC trolleybus can demand, a set of constraints and conditions describing the trolley-grid and the behavior of the trolleybus called the estimator has to be developed. There are multiple information the state of the grid estimator should provide to the BMS. In order to be as accurate as possible in determining the availability of power, an idea of what the traffic currently is seems to be crucial. Knowing if vehicle is alone on the section or sharing it with other vehicles is basis for predicting what the IMC trolleybus can demand. Further stages of the estimations have to go after measurements of current and voltage the IMC trolleybus can collect on the route. Understanding the measurements can provide an insight into the behavior of other vehicles and their effect on the substation as well as overhead lines. Having stated these, first research question can be formulated as:

Research Question 1

How can the already available bus measurements estimate the available power capacity in the trolley grid?

The first research question is of a theoretical nature and will be answered in chapters 3 and 4. To come to such conclusion, historical measurement data of trolleybus operation as well as trolley-grid section topology or extreme operation cases will be investigated. The findings will be used to come up with a set of equations and rules that can estimate the state of the trolley-grid and its condition for the purposes of the Valley-Charging approach for IMC vehicles. The results will serve as a basis for the Arnhem case study, where a diesel trolleybus line will be transformed into an IMC one. Extra load will be thus added to the trolley-grid. The relevance of the research comes from the question whether the Valley-Charging approach makes the new IMC line operable and it should address any potential drawbacks for employment of this new technology.

The results of the first research questions, which will be the estimator, needs to be validated. The estimation methods are generic and can be used for every trolley-grid system. Even though the results of the first research question are related to Arnhem as input data from this city were used, the methodology and calculations can be used with any other trolley-grid data. It is very necessary to provide a general estimator methodology so the Valley-Charging approach can be also studied in other trolley-grids as well.

Research Question 2

How will estimator-supported Valley-Charging approach help to increase the penetration of IMC trolleybuses in terms of energy collected and limit violations?

The second research question is of a practical nature as it includes a case study of Arnhem trolley-grid. Line 352 in Arnhem is currently operated by a fossil fuel powered buses. It is an interurban connection meaning that it connects the municipality of Arnhem with municipality of Wageningen. To make the line sustainable, it is transformed into IMC line. As it is going to share route with other line of regular trolleybuses, it is likely that their power demand collision could be problematic. The IMC trolleybuses of line 352 will be equipped by the estimator which provides charging power predictions for Valley-Charging approach. The case study will serve also for studying the success rate, or more precisely accuracy, of the estimator.

The simulations of the case study need to show how reliable is the application of the estimator with regards to the technical limits of the trolley-grid. Results will be analyzed to detect problematic spots and estimator malfunctions to push the development of the estimator forward.

At the same time, it is of great importance so that the estimator can secure enough energy to be collected and stored in the on-board battery to make it through the autonomous part of the route. The estimator needs to make sure the amount of energy collected under the overhead lines is at least equal to the energy that will be discharged off the trolley-grid.

These objectives mentioned needs to be met with the help of the estimator. MATLAB simulations will be used to run the whole day operation to see whether the newly electrified line is operable with the help of Valley-Charging approach supported by the estimator.

1.6. Thesis Structure

This Master thesis has following structure:

- **Chapter 1 - Introduction**
  Introduction to In-Motion Charging (IMC) technology and to the concept of Valley-Charging with stating the problem and research questions
- **Chapter 2 - Literature Review**
  Studying previous research in the field of IMC technology and defining the research gap
- **Chapter 3 - Methodology**
  Explanation of the calculations used and description of the modelling techniques and processes
- **Chapter 4 - Early Valley-Charging Estimator Versions**
  Results of development process of versions of the estimator to support the Valley-Charging scheme
- **Chapter 5 - Arnhem Case Study**
  Arnhem Case Study results with the final version of estimator
- **Chapter 6 - Conclusion**
  Conclusion and recommendation for future research work

2

Literature Review

This chapter aims to examine the literature on In-Motion Charging (IMC) systems and to determine the gaps in the existing research. In section 2.1, the necessity for electric mobility will be clarified. Section 2.2 presents the shift towards the IMC technology. The literature on on-board battery storage will be studied in section 2.3 as well as choice of the most suitable battery type for IMC will be justified. Section 2.4 looks at recent IMC case studies to get insight to parameters such as charging power or catenary length. The research gap will be illustrated in section 2.5.

2.1. Electric Mobility

The public transport is believed to be an indicator of social welfare [29]. On top of that, the level of urbanization has been steadily increasing and will reach 66% in 2050 as people tend to move to cities [25]. It can be therefore expected that its transportation network will be further extended. However, expansion of the fossil-fuel based Bus Public Transport (BPT) as we know it today is in contrast with the aim of the European Union (EU) to reach carbon neutrality.

Studies have agreed on electric mobility being the key path for the transformation of public transport segment energy-wise [36, 10]. This is especially true for BPT which is still yet to undergo this energy transition. For this reason, there has been an increase in the electric buses (e-buses) purchased over the last years [6]. Bergk et al. [10] looks at the comparison of diesel buses and the e-buses (with opportunity charging and over-night charging) in terms of their energy consumption. His findings are captured in table 2.1. It is straightforward that the diesel bus is the least efficient mean of BPT as its energy consumption per kilometer is more than double than of the e-buses. Moreover, he claims that the efficiency of the vehicles will generally further increase. Decrease of the energy demand can be seen as a massive advantage of e-buses taking the current energy crisis into consideration.

Table 2.1: Average energy consumption comparison of bus public transport solutions. OC = Opportunity charging, ONC = Over-night charging. Partially adopted from [10]

Drivetrain Concept	Unit	2015	2025
e-bus with OC	kWh/km	2,1	1,9
e-bus with ONC		2,4	2,2
Diesel bus		5,2	5,0
Trolleybus		1,6	-

Kühne [22] sees the advantages from a different perspective. He states that idling is the most frequent speed of BPT. The diesel engine thus consumes a lot of energy unnecessarily, while electric engines can stop revolving having no energy losses at standstill. The regenerative braking is beneficial in two ways. It improves the energy consumption as can be seen from table 2.1 and also at the same time helps to brake which significantly extends the mechanical brake's lifetime. To support also the rise of the social welfare, his paper suggests following aspects in favor of public transport electric vehicles: Locally emission free, less noise, longer lifespan. With electrical renewable energy sources penetrating the energy mix in Europe, the direct use of energy by charging electric vehicles is perceived as the most efficient [22, 10].

2.2. In-Motion Charging Technology

Even though e-buses live up to the expectations and reduce the greenhouse gas emissions and energy consumption of the public transport, Bartłomiejczyk & Połom [6] looked at their downsides. They reported that the usage of electric buses lead to increased initial investment cost as the e-bus fleet has to contain more vehicles than the one of internal combustion engine buses. The battery pack to cover the all-day shift would be inadequately large and heavy, so they have to make regular long stops to recharge. This is due to the limited range of e-buses constrained by the on-board battery capacity despite the fact these technologies have marked rapid improvement in the last decade. Based on these findings, Bartłomiejczyk & Połom propose trolleybuses as a vital tool to meet the requirements of sustainability in public transport and to mitigate the aforementioned issues of e-buses. Trolleybuses already used to fulfil the local decarbonization goal of public transport but were abandoned with the availability of cheap fuel for internal combustion engine buses [7]. Expert would also discard this vehicle type due to its dependency on the overhead catenary system [7, 14].

The studies performed by Bartłomiejczyk [2], Bergk et al. [10], or Sun et al. [30] suggest employing In-Motion Charging (IMC) technology (sometimes also referred to as dynamic charging or Slide-In system) which combines the benefits of both e-buses and trolleybuses. In such system, part of the route is covered with overhead lines, whereas the rest has no contact points with the trolleygrid at all [2]. At the former section, the overhead lines are used as the power source for traction and also for charging the on-board storage. At the later section, the vehicle uses this battery to propel the vehicle and it operates independently on the catenary.

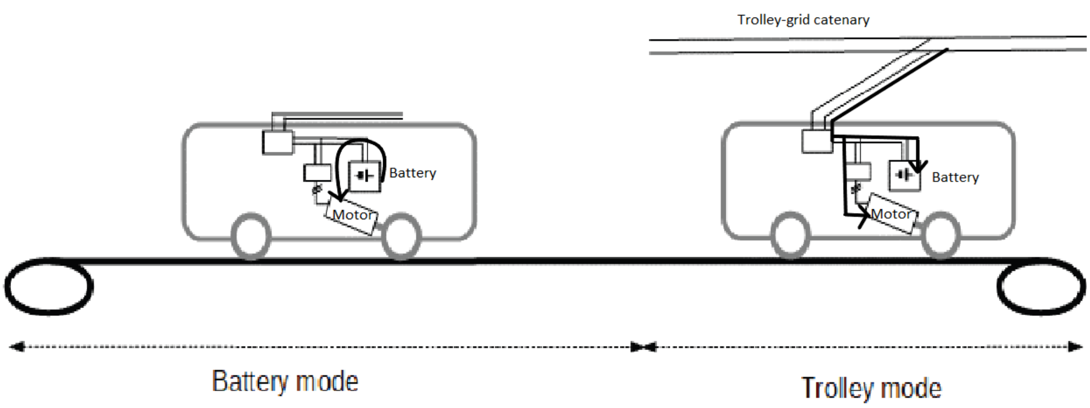


Figure 2.1: The idea of In-Motion Charging [2]

Even though the IMC technology seems promising as a replacement of diesel buses, researches tend to leave it out of their public transport electric vehicles feasibility studies. The study of Vilppo & Markkula [33] only count with conventional e-bus charging strategies such as depot, end-stop and line-stop charging. Randhahn et al. [28] only consider depot and opportunity charging while leaving out the IMC for being partially dependent on the catenary. On the other hand, the paper of Beekman [9] sees IMC as a great compromise between flexibility and sustainability as the bus operator can change the route easily due to the autonomous mode but still the vehicle uses electric energy. Bartłomiejczyk [3] backs this opinion in his work and also adds that IMC reduces the size of the fleet as the vehicles do not have to be excluded from operation for charging purposes. As one of the reasons to abandon trolleybuses was the visual aspect, IMC no longer has this issue as the trolleygrid segments can be placed on remote places with no sights [7].

2.3. IMC On-board Battery

For electric vehicles, just like the IMC, the on-board storage is a crucial component [16, 32] that determines the nature of the vehicle and its operational properties. Not only does the use of EVs indicates the requirements for the power source, but also the battery itself is only suitable to some EV applications due to the materials used for battery cells and their chemical behavior. To ensure the most convenient IMC trolleybus operation, a good match of battery and the driving pattern has to be designed.

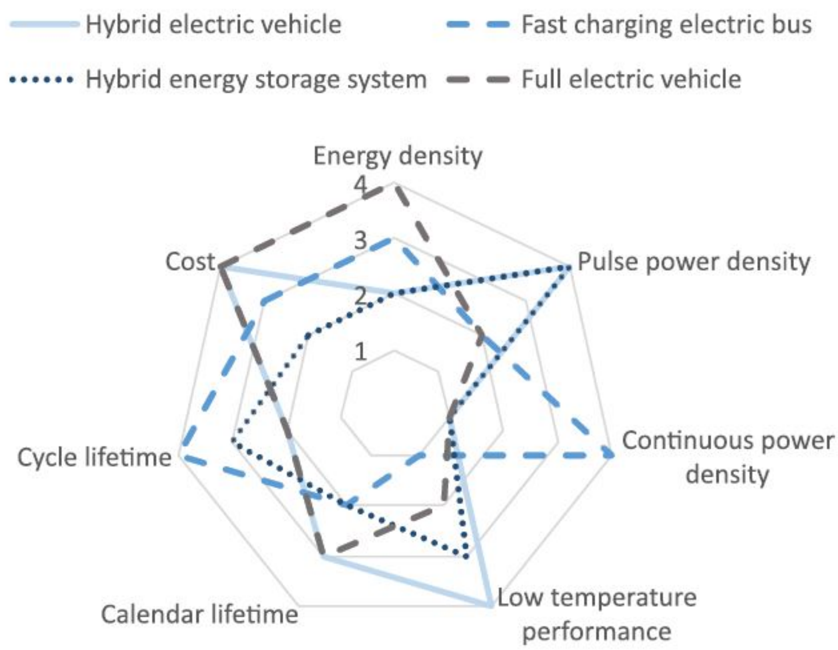


Figure 2.2: Importance of battery parameters based on its application (4 - the highest importance, 1 - the lowest importance). To IMC trolleybus, *Fast charging electric bus* parameters suit the most [26]

The IMC trolleybus has its specifics in terms of battery choice.

- Energy Capacity

  An electric bus has to cover the whole route energy demand with its battery. If the short opportunity charging at terminals is not taken into account, the battery should provide energy for the whole day. For vehicle, this accounts for just a fraction of the route without the overhead lines (typically 60-80%) and the battery is recharged multiple times a day when going under the overhead lines. The IMC battery can thus have considerably lower capacity (45 [kWh] in Solingen, DE) than full battery electric bus (348 [kWh] in London, UK) [16, 7, 27] but higher capacity than auxiliary batteries of today's trolleybus [10]. This results in reduced battery size/mass and improved economy of the vehicle.

- Energy Density

  To have a battery that can provide the necessary energy on all occasions and at the same time keep the size the lowest, it is desirable to use a battery with high energy density. It is the ratio of energy capacity and the mass in [kWh/kg]. The higher the energy density is, the lower the mass of the battery pack for a particular capacity. The benefit can be twofold: improved energy efficiency by choosing the battery with low mass or increased vehicle range by having higher capacity for the same mass.

- Charging Power

  The two charging approaches used the most by electric buses are over-night and opportunity charging. The former stands for out-of-operation depot charging. As the time to recharge could be several hours at night, the charging power does not have to be that high. Whereas for the opportunity charging, the time is significantly limited by the circumstances (standing at the terminal station to change direction) and the charging power is higher. IMC charges en route and only under the overhead lines. The charging time is limited (minimized) by the time spent under the charging corridor which means the charging power has to be maximized [2, 3]. It follows that the key aspect of the on-board storage will be its charge and discharge capability, the so-called C-rate to be able to withstand high charging and discharging power. The discharge rate is related to acceleration and traction purposes, whereas the charge rate stands for the battery charging either via the overhead lines or by recuperation [32].
  The latest technologies implemented for IMC reach charging power of 500 [kW] [26, 20] where 240 [kW] accounts for direct battery charging [20]. The C-rate is seen (mentioned as *"Continuous power density"* in figure 2.2) as the most important aspect for *"Fast charging electric bus"* (which is similar in properties to IMC trolleybus) [26]. It also emphasises the cycle lifetime as the high frequency of charging can negatively affect the lifespan of the storage.

- Depth of Discharge

  As IMC vehicle is charged under limited, or more precisely minimized, charging corridor, which can be segmented, a repetitive charging cycles can be expected during one trolleybus ride. The Depth of Discharge (DoD) [%] is usually mentioned in battery's technical specification and represents the lower operational limit of the State of Charge (SoC) [%]. The higher the DoD is, the more energy can be stored. With regards to the IMC application, it means that the trolleybus can both cover longer distance in the autonomous mode and also under the overhead lines charging the IMC battery. While this factor determined by the manufacturer stands for the technical limits, the DoD stated by the public transport operator may be lower to secure a reliable operation.

All the parameters mentioned in the previous text, such as energy density, C-rate or cycle lifetime, depend on the battery chemistry. The preferred battery technologies have been changing since the emerge of batteries as the development continuously brings new manufacturing methods and materials. The first batteries used for trolleybus autonomous traction deployed cells like lead [7, 27], nickel-cadmium (NCd) [7, 27, 36] or nickel-metal hydrid (NMH) [7, 27, 36]. However, several sources agree that it was the large-scale diffusion of Lithium-Ion (Li-Ion) battery technology that made electric mobility feasible when it replaced the obsolete battery cells [14, 7, 27, 36] as well as making IMC implementation possible. Li-Ion technology is superior in terms of energy and power density [35, 24, 32] and cycle lifetime [24, 37].

The work of Tomar et al. [32] looks into the Li-Ion batteries in terms of their cathode and anode materials. Each Li-Ion type has slightly different properties. While there are many different cathode materials, such as Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO) or Lithium Iron Phosphate (LFP), the most commonly used anode material nowadays is carbon [32]. However, an example of an alternative anode material Lithium Titanate Oxide (LTO) is given [32]. From table 2.2 it can be seen that LTO anode has the advantage especially in power capabilities, thermal stability and safety. On the other hand, its cells have lower voltage and the purchase cost is slightly higher than of those with carbon anode. As this particular anode is considered eligible for general EV use by several references [17, 32, 26], this Li-Ion battery type will be further investigated in section 2.3.1.

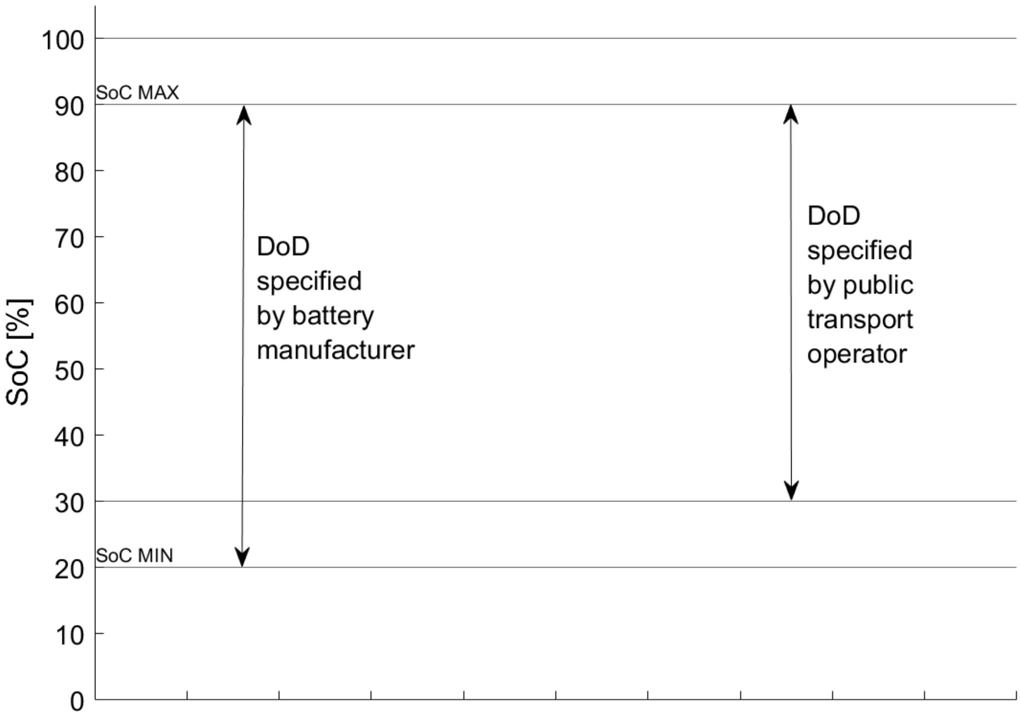


Figure 2.3: Depth of Discharge (DoD) of IMC on-board battery illustration

Table 2.2: Characteristic properties of Li-Ion batteries with different cathodes and anodes (cathode/anode). ”+” - positive, ”-” negative, ”0” - neutral. [32]

Characteristics	LMO/C	NMC/C	LFP/C	*/LTO
Voltage	+	+	- -	- - -
Energy Density	-	+	++	- - -
Power Density	++	++	+	++
C-rate	0	0	+	++
Thermal Stability	-	+	++	+++
Safety	++	+	+++	+++
Lifespan	-	+	++	+++
Cost	++	+	+++	-

2.3.1. Lithium Titanate Oxide Battery

One of the latest generations of Li-Ion batteries is the Lithium Titanate Oxide battery [38]. It uses the lithium titanate oxide ($\mathrm{Li_4Ti_5O_{12}}$) as the negative electrode instead of the usually used graphite (C). LTO anode can be combined with cathode materials such as LCO [15], LMO [15] or one of the most common LFP [15, 32] to create a Li-Ion battery. Considering all the general positive and negative aspects of the LTO anode, choosing the cathode material modifies the cell’s properties and each is suitable for different application.

The LTO is a spinel structured oxide [26, 15], which makes it thermally and chemically stable [34]. One of the spinel’s attribute is its acid-base and redox property which makes it directly suitable for cycling chemical reactions [34], typical for batteries. The cycle of lithium extraction and insertion can be described by following chemical equation:

$$Li_4Ti_5O_{12} + 3Li^+ + 3e \Leftrightarrow 2Li_7Ti_5O_{12} \quad (2.1)$$

The spinel structured LTO ($Li_4Ti_5O_{12}$) turns into a rock-salt state LTO ($Li_7Ti_5O_{12}$) after accepting 3 lithium ions to its structure [15, 26]. This electrochemical reaction has a capacity of 175 [$mAhg^{-1}$] [15, 26, 21]. It is necessary to mention that this theoretical capacity can be reached when operating the battery cell in a redox potential range of 1-3 [V] [15, 26, 21]. However, research has shown, that the capacity and thus the energy density of LTO cell can be increased by extending the voltage range to as close to 0 [V] as possible to almost 293 [$mAhg^{-1}$] [15, 21].

Compared to battery cells with graphite anode, the LTO based cells have significantly lower nominal cell voltage, up to 1,4 [V] compared to graphite [26], due to their higher redox potential to Li (1,55 [V]) [26, 32]. It goes hand in hand with rather poor energy density. In particular, low voltage means that more battery cells have to be connected together to achieve an acceptable battery voltage and energy density [26], which can result in heavier battery pack on-board. On the other hand, operating at lower voltage significantly increases the safety [26]. Carbon anodes with higher nominal voltage are prone to several undesirable chemical processes, such as dendrite formation or Solid Electrolytic Interface (SEI) creation [26, 15]. The firstly mentioned might lead to a short-circuit of the electrode [15]. The latter is characterized by electrolyte settling on the anode's surface which poses a problem for insufficient Li ions extraction/insertion. Also, the chemical process described by equation 2.1 comes with almost no volume change of the electrode which is not the case for carbon [26, 15, 17]. As LTO anode does not suffer from these deficiencies, it benefits from great cycling stability as well as cycle lifetime [26, 15, 17]. As can be seen in table 2.2, the LTO battery show excellent thermal properties. This is also beneficial for the IMC application as the trolleybus is operated with no respect to the ambient temperature. One of the drawbacks is the price which is unfavourable for LTO compared to wide-spread carbon-based Li-Ion batteries. However, higher expense on the battery can be compensated by the above-mentioned longer lifespan.

The paper of Vilppo & Markkula [33] performed a comparison of two battery technologies, LFP and LTO. They investigated the battery's performance under different charging schemes, namely depot charging, end-stop charging and line-stop charging. Although the IMC technology was not included, the results are still applicable as these charging types still use fast charging with high power. The conclusion said that the LTO battery is the best investment option when fast charging and slow over-night charging is deployed, which is exactly the case of IMC. Long cycle-life was named as the most important reason to choose this kind of battery.

The IMC trolleybus is special in terms of battery choice. Its operation based on fast charging en route with power of lower hundreds [kW] under the overhead lines requires good power properties. Moreover, the nature of public transport demands great safety, reliability and long lifetime to keep the fares as low as possible to make it affordable. Having said that, it is clearly visible that the LTO battery suits the IMC application especially thanks to its high C-rates and good endurance.

2.3.2. Battery Modelling

To successfully study IMC, the on-board battery needs to be modelled to simulate its operation. There are several methods proposed in literature from 3 categories: electrochemical, mathematical and electrical models. Li & Tseng [23] look at their comparison. While electrochemical models are the most precise ones, they suffer from their complexity, time demand and extensive knowledge required to build them. Mathematical models tend to be easier to set up but may be inaccurate for some applications. Electrical models use equivalent circuits consisting of voltage sources, capacitors and resistors to represent the battery's behavior. They are the most frequently used. Furthermore, SoC parameter is not ideal to follow the available energy and State of Energy (SoE) is proposed as the ratio of the energy left in the battery and the maximal energy content as an alternative. In the end, the electrical equivalent circuit model was used to determine the SoE.

The research of Huang et al. [18] inspects the types of equivalent circuit battery models. While PNGV model is the most accurate one, Rint, Thevenin and Second-Order models also bring acceptable results for electric vehicle modelling. Immonen & Hurri [19] model the LTO battery for electric car using the Second-Order equivalent model. Yao et al. [38], on the other hand, use mathematical model for the same battery type.

2.4. In-Motion Charging System Parameters

The purpose of this section is to determine the magnitude of the most suitable parameters of the IMC system as well as inspect their relationship. It includes charging power, overhead lines and battery capacity.

Charging Power

The charging power is an essential parameter for the IMC system. Bartłomiejczyk [3] states that the main limitation of the charging power used to be the battery pack, or more precisely its rather low C-rates. As it was explained in section 2.3, he now does not see the cell technology as an issue as the capability of reaching high C-rates is more common. For instance, 5C charging current for 100 [kWh] battery would result in 500 [kW] of charging power. However, he further states that it is now the current collector, that trolleybuses use to feed the vehicle from the overhead lines, which represents the main limitation. Despite the technical limit of current collectors is 600 [A], the maximal charging current should not exceed 200 [A] while moving and 100-150 [A] while standstill according to his findings. This is due to the thermal stress of the cables. As the current flows, transmission losses in the form of heat occur and cooling gets difficult when the vehicle is not moving. To contradict these current limit values, the technical sheet of Vossloh Kiepe's latest IMC vehicle [20] claims that there can be a power transfer of 500 [kW] from the trolleygrid to the vehicle. In other numbers, that would mean a current of 833 [A] (grid voltage of 600 [V]) or 714 [A] (grid voltage of 700 [V]).

Also the line voltage may be affected by the charging power. By performing a simple calculation according to the following equation:

$$V_{\mathrm{b}} = \frac{(V_{\mathrm{s}} + \sqrt{V_{\mathrm{s}}^2 - 4R_{\mathrm{b}}P_{\mathrm{b}}})}{2} \tag{2.2}$$

V_{b} . . . . Voltage at the point-to-point connection bus-trolleygrid [V]
V_{s} . . . . Substation nominal voltage [V]
R_{b} . . . . overhead line resistance between bus and substation [Ω]
P_{b} . . . . Bus power drawn from the overhead lines [W]

Table 2.3: Voltage of the point-to-point connection bus-trolleygrid based on the bus power drawn from the grid and the overhead line resistance. The resistance value changes based on the distance of the bus from the substation. Substation nominal voltage is 700 [V]

Charging Power [kW] \ Resistance [Ω]	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09	0,10
50	699,3	698,6	697,9	697,1	696,4	695,7	695,0	694,2	693,5	692,8
100	698,6	697,1	695,7	694,2	692,8	691,3	689,9	688,4	686,9	685,4
150	697,9	695,7	693,5	691,3	689,1	686,9	684,7	682,4	680,2	677,9
200	697,1	694,2	691,3	688,4	685,4	682,4	679,4	676,3	673,3	670,2
250	696,4	692,8	689,1	685,4	681,7	677,9	674,0	670,2	666,2	662,2
300	695,7	691,3	686,9	682,4	677,9	673,3	668,6	663,8	659,0	654,1
350	695,0	689,9	684,7	679,4	674,0	668,6	663,0	657,4	651,7	645,8
400	694,2	688,4	682,4	676,3	670,2	663,8	657,4	650,8	644,1	637,2
450	693,5	686,9	680,2	673,3	666,2	659,0	651,7	644,1	636,4	628,4
500	692,8	685,4	677,9	670,2	662,2	654,1	645,8	637,2	628,4	619,3

Table 2.4: Voltage of the point-to-point connection bus-trolleygrid based on the bus power drawn from the grid and the overhead line resistance. The resistance value changes based on the distance of the bus from the substation. Two vehicles on the section, one located at section with 0.05 [Ω] resistance, the other changing position. Substation nominal voltage is 700 [V]

Charging Power [kW] \ Resistance [Ω]	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09	0,10
50	674,2	672,7	671,1	669,5	667,9	666,4	664,9	663,3	661,8	660,2
100	667,0	664,6	662,2	659,7	657,2	654,9	652,5	650,2	647,8	645,3
150	659,6	656,4	653,1	649,7	646,2	643,0	639,7	636,4	633,1	629,7
200	652,0	647,9	643,6	639,2	634,7	630,5	626,3	622,1	617,7	613,3
250	644,3	639,2	633,9	628,4	622,7	617,6	612,3	607,0	601,5	596,0
300	636,4	630,3	623,9	617,2	610,2	604,0	597,6	591,1	584,4	577,5
350	628,4	621,2	613,6	605,6	597,0	589,6	582,0	574,2	566,1	557,7
400	620,1	611,7	602,9	593,4	583,1	574,4	565,4	556,0	546,3	536,1
450	611,6	602,0	591,7	580,6	568,4	558,2	547,6	536,4	524,6	512,2
500	602,8	591,9	580,1	567,1	552,5	540,7	528,1	514,8	500,5	485,0

The magnitude of the voltage drop based on the bus power and the distance of the vehicle from the feeding substation represented by the resistance can be investigated. It can be seen from table 2.3 that the maximum charging power has to be selected wisely in order not to put the grid into jeopardy. If we take the already mentioned 500 [kW] power, the voltage drop is only 7,2 [V] while very close to the substation whereas it is more than 80 [V] when the vehicle is far. Taking into consideration that the voltage limit of 700 [V] grid might be 500 [V], 80 [V] is already pushing the grid to half of its limits. Table 2.4 shows what the voltage drop is when two vehicles are on the same section. They both draw the same power, one is always positioned with 0.05 [Ω] resistance, the other is changing its position. It can now be seen that the voltage drop is much more serious with two vehicles, especially when they are drawing high power. On top of that, 0.1 [Ω] is equivalent to approx. 600 [m] distance from the feeder cable. This can be reached in vast majority of trolley-grid sections which can go even go over 1.5 [km] in length. Bartłomiejczyk & Połom [8] suggest using bilateral trolleygrid where 2 substations power the section, thus reducing the distance of the vehicle from the feed-in point. They also emphasize the fact that such system is more favorable to regenerative braking utilization as also vehicle connected to the neighbouring section can take the excessive power and improve the efficiency of operation.

Another solution may be found in Valley-Charging approach. The basis of this charging scheme is load shifting to moments when the substation can provide enough power. Such smart charging scheme would evaluate the current parameters of the grid and the vehicle and the power drawn from the catenary would be adjusted accordingly. To achieve this, the charging power would change over time to always meet the requirements of the trolley-grid. In situations of high trolleybus traffic intensity, a significant electric load on the traction network may cause excessive voltage drops [2] and push the section towards its operational limits. This can be for example the case of Arnhem Centraal Station, where majority of trolleybus lines goes. Valley-Charging charging can lower the charging power even up to 0 to secure safe trolleygrid operation. On the other hand, conventional charging schemes using constant charging powers might exceed the technical limits as they have no mechanism to react to state of the grid.

Figure 2.4 clearly shows the difference between the conventional methods and the proposed Valley-Charging method. While the conventional charging scheme would still continue charging the predefined power even though the substation might be beyond its power demand limit, the Valley-Charging scheme reacts and curtails its charging power and shifts its demand to help the substation.

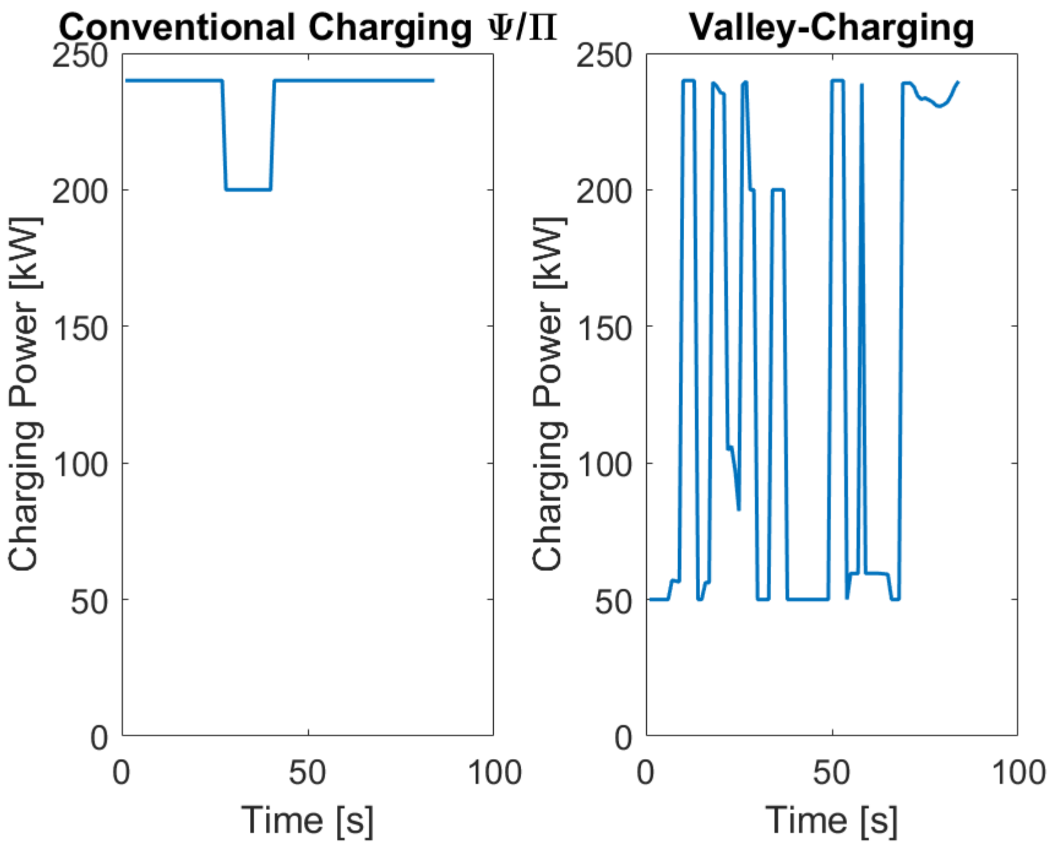


Figure 2.4: Charging Power of conventional IMC charging schemes and Valley-Charging method. Conventional scheme (in this example 240/200, Ψ/Π) keeps charging powers constant based on in-motion or standstill. Valley-Charging can change the charging power over time and prevent the trolley-grid from failures

Overhead Lines Coverage

The trolleybus infrastructure and its maintenance, including the overhead wires, represents a non-negligible part of the system integration budget [16, 22]. Díez [14] says that the infrastructure costs for IMC are indeed high but the studies do not take already existing tram/trolleybus networks into account which can deploy this technology much easier and with rather negligible costs. It is necessary to note that there are more than 300 existing trolleybus networks [7] and many more tram networks worldwide which can directly make use of this technology.

It is still desirable to minimize the charging corridor length. Bartłomiejczyk [2] looks at the minimal coverage length for the use case of Gdynia, Poland. However, the result of 32% may not be accurate. His calculation is based on the average velocity of the vehicle under the charging corridor. To question this approach, let's take 20 [km/h] as the average velocity. Assuming that the charging scheme allows 100 [kW] in-motion battery charging, 50 [kW] while standstill and the operation lasts 1 hour, we can arrive at ambiguous results:

20 km/h for 1h	40 km/h for 0,5h and standstill for 0,5h
E = $P_{ch,m} * t$ = 100*1 = 100kWh	E = $P_{ch,m} * t_1 + P_{ch,s} * t_2$ = 100*0,5 + 50*0,5 = 75kWh

The fact that the average speed can be achieved in two different ways caused the results of picked-up energy to vary. In the latter case, the vehicle might not receive enough energy to cover the autonomous section and the simulation would be evaluated as fail.

In a more recent article, Wołek et al. [36] continue in the Gdynia case study and show how the minimal coverage rate is also affected by the traffic speed. They take two charging schemes into account. Firstly, 120 [kW] in-motion, and then 250 [kW] in-motion, while the maximum power during idle run was 80 [kW]. The results are presented in figure 2.5. It is evident that the higher the average speed is, the lower the time to pick the energy up is, hence the length of the overhead cables has to be increased. With the average speed in Gdynia of 14 - 18 [km/h], they came to a result of 30 - 35% for 120 [kW] and 20% for 250 [kW].

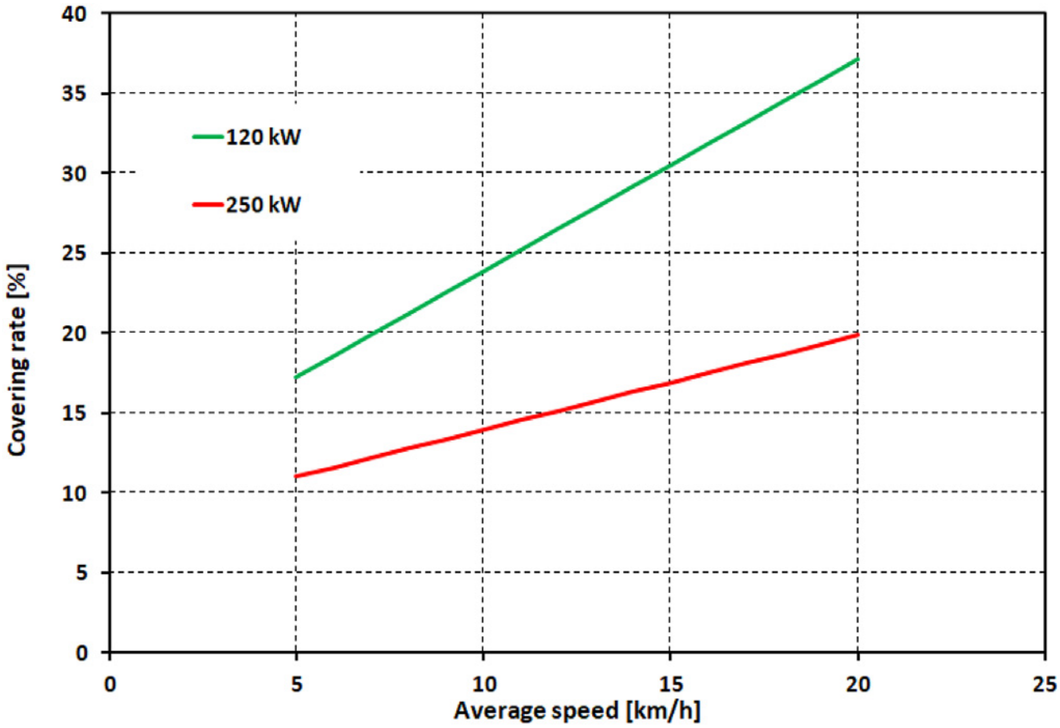


Figure 2.5: Minimal coverage rate for two charging methods based on the average speed along the charging corridor. Green line - 120 kW, red line - 250 kW. Both methods can charge only 80 kW while standstill. [36]

The latest paper presented used yearly average energy consumption of the vehicle to calculate the minimal coverage rate. However, the energy consumption can be much larger especially in winter time due to heating. Alike method was selected by Díez [14] who also neglected the HVAC for his case study of IMC system of Quito, Ecuador. He was able to reach impressively low coverage rates of around 5% which were unfortunately compensated by unrealistic depot charging power of 1,4 [MW]. His minimum cost scenario included two electrified segments (14% of the route), 68 [kWh] battery, depot charging of 47 [kW] and only 50 [kW] IMC. Most of his scenarios worked with 20% coverage, which seems reasonable, but with the HVAC included this number would be higher. Another work of Bartłomiejczyk [3] accounts for this aspect and presents figure 2.6. This proves the necessity to include the seasonal change of energy consumption.

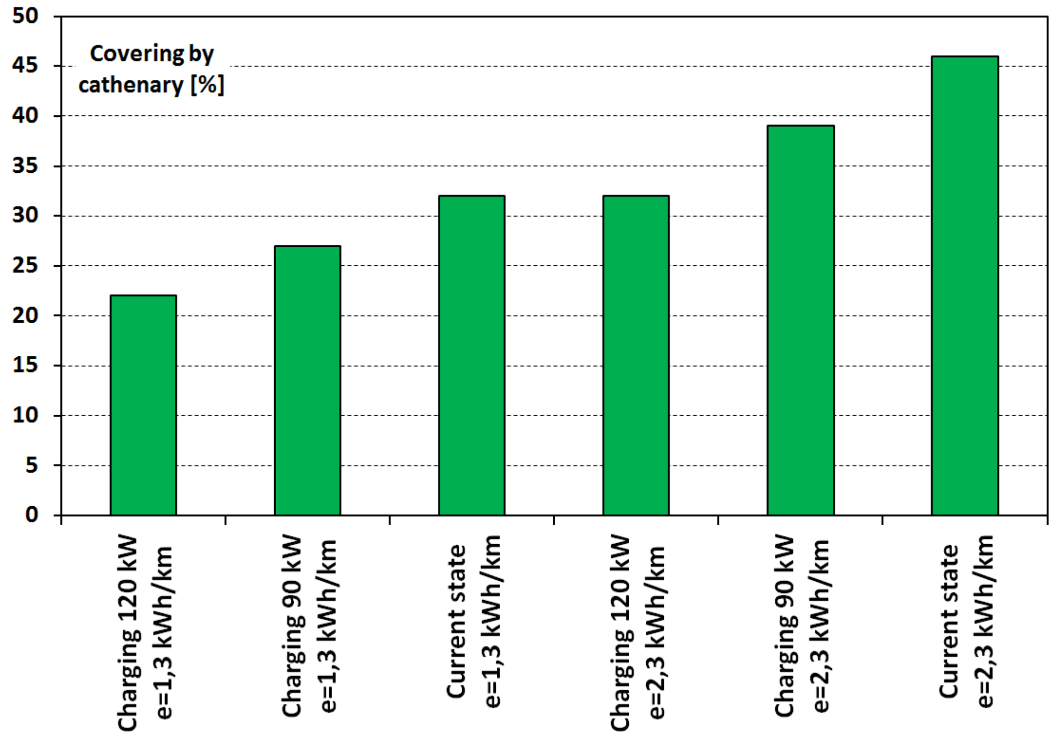


Figure 2.6: Minimal coverage rate for 120 kW and 90 kW battery charging power and 1,3 kWh/km (summer) and 2,3 kWh/km (winter). [3]

Overhead Lines Segmentation

Vast majority of all studies on IMC only deal with the minimal coverage length but omit the spatial structure of the trolleygrid. It can either mean the segmentation of the charging corridors into smaller sections or determining the most suitable placement of the sections with overhead lines based on the route topography, traffic and the power system.

In one of their work, Bartłomiejczyk & Połom [5] explain the effect of catenary spatial differentiation. The principle is demonstrated in figure 2.7. The upper picture 2.7a shows how the trolleybus line can be divided into segments. While the "*Dynamic charged electric bus variant 1*" uses only one charging corridor, "*Dynamic charged electric bus variant 2*" deploys two shorter segments. The influence is visible in figure 2.7b, where the battery charge level can be seen. The variant 1 evidently requires higher battery capacity to cover the distance in autonomous mode, whereas the SoC in variant 2 will oscillate much less. By suitable placement of charging corridors, the battery pack can be reduced, making the operation more efficient, both energy- and cost-wise.

Another special case of line segmentation is the so-called range extension (figure 2.8). This application of IMC is mentioned in [31] as an opportunity to expand the existing trolleybus lines beyond the existing trolleygrid without the necessity to invest into new infrastructure. Another source [1] deals with range extension, but alike the previously mentioned, they both care about the battery sizing instead of the IMC system as a whole.

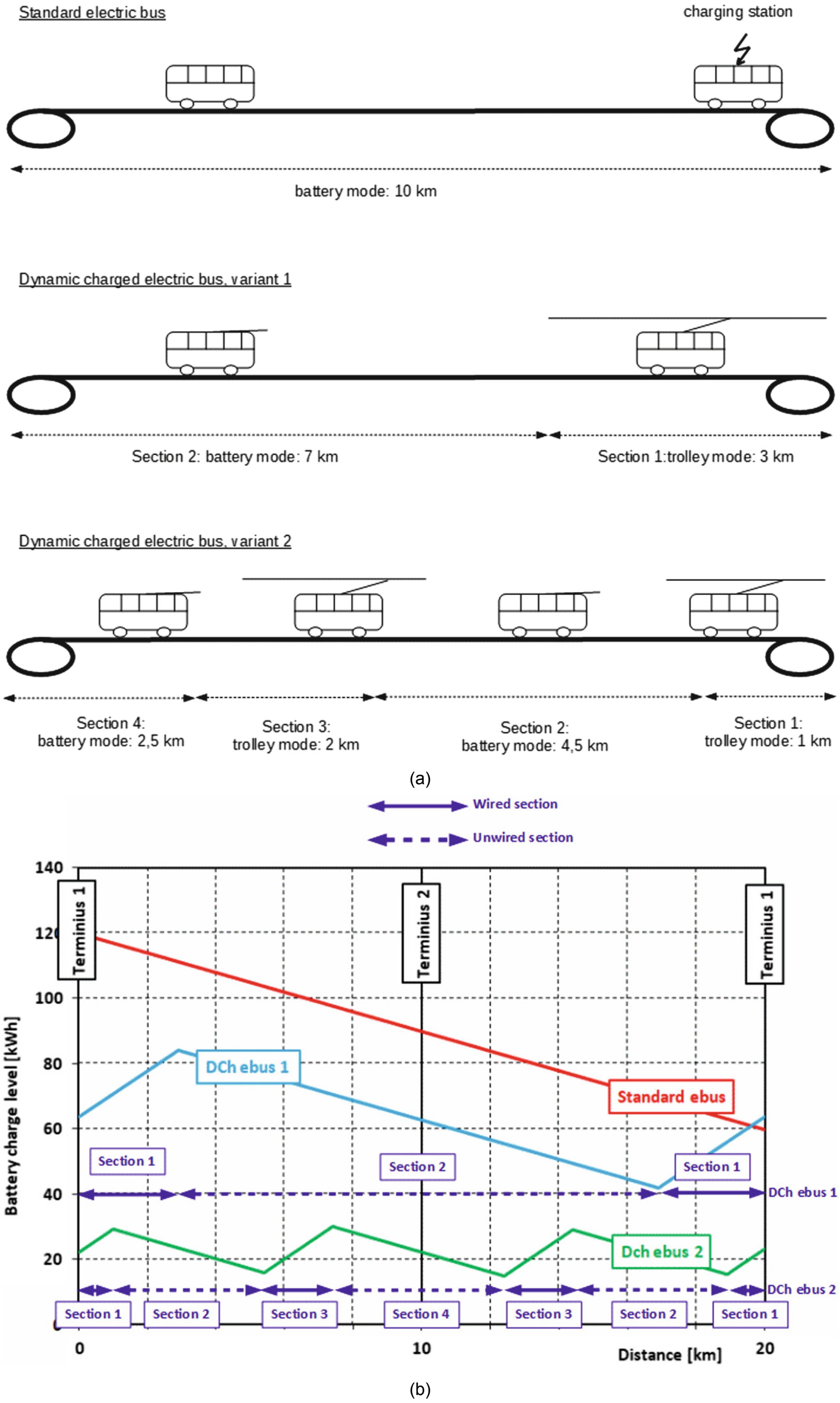


Figure 2.7: (a) Example of route operated by standard electrical bus and two variants of dynamic charged buses (b) Diagram of battery charge level during operation of route by standard electrical bus and two variants of dynamic charged buses [5]

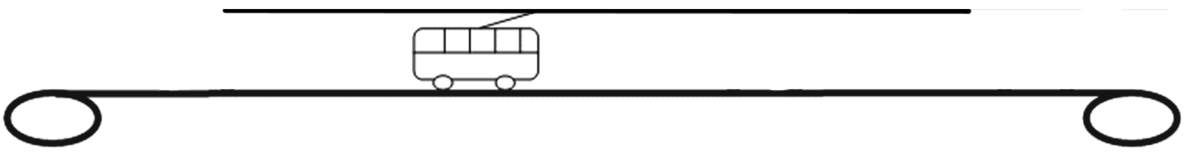


Figure 2.8: Range extension using IMC trolleybus

Few researchers also advise on placement of electrified sections as a subresult of their initial work. Bergk et al. [10] states that it is convenient to build the charging corridor along a section with low average speed as it results in longer time spent under the catenary charging the battery, which in turn can reduce the necessary length of the overhead lines. It should be further noted that by choosing suitable construction location, the investment costs can be significantly reduced. Bartłomiejczyk & Połom [8] also agree by saying that the section along dense traffic routes are the most favorable. On top of that, they add the recouped energy receiving probability as an important factor. Where there is a lot of braking, there should be a charging corridor with bilateral connection to utilize the energy better, either by storing it in an own on-board storage or transfer it via the overhead lines to other buses connected to the particular section.

The case study of Quito, Ecuador by Díez [14] looked deeply at the placement of the electrified sections. Out of his 160 scenarios, two segments were electrified in almost all of them. The reason was the high gradient of the road, which increased the energy consumption from the average 1,34 [kWh/km] up to 3 [kWh/km]. Here the vehicle would use 33% of all the energy needed. It was also noted regenerative braking energy can be utilized better in the line section with smoother slope. Along one of the climbing sections, the energy consumption was 5,5 [kWh] while going uphill and only 1,7 [kWh] was recouped while going downhill. The simulations, however, were performed in segregated operation mode, meaning there was no interference with the traffic. The real-life energy consumption as well as the number of segments electrified could be different.

2.5. Research Gap

There are studies on IMC that compare this technology to other means of BPT in terms of energy consumption. Simulation papers' results usually limit their findings to whether the implementation of IMC is feasible or not.

Most of the papers deal with the catenary coverage from the perspective of the minimal coverage length to successfully operate the particular trolleybus line. This ratio, however, does not provide the information on where the cables should be placed. It was demonstrated in section 2.4 how the placement and segmentation of electrified sections have to be taken into account. The work of Díez [14] certainly brought new insight into this problematic, but his methodology was limited in the sense of not accounting for HVAC power and considering a separate off-traffic operation. This thesis will look at how the correct placement can further reduce the length of the charging corridors by suitable positioning while including seasonal changes in energy consumption as well as real-life traffic data.

Battery will be modeled to extend the trolleybus model and transform it into an IMC vehicle. The LTO battery has been found the most suitable for high-power and high-current applications. Even though wide range of temperatures can occur throughout the year under European conditions, thermal behavior of LTO battery does not have to be modelled as the technology shows superior stability. Also, cooling or heating will be omitted. Therefore, the battery will be modeled mathematically to determine the amount of energy charged and discharged based on the charging and discharging power.

When simulating the charging scheme, researchers tend to use no more than two different charging powers, one for a moving vehicle and another for an idling one. Valley-Charging approach with charging power varying over time based on the trolleygrid state has not been introduced in any of the models. Yet, this approach can play an important role in IMC diffusion. Speaking particularly about the city of Arnhem, the already existing trolleygrid is now being used to extend the range beyond the city's borders. The feasibility of this charging scheme for such public transport lines will be investigated.

3 Methodology

Chapter 3 describes the methodology of the estimator supported Valley-Charging research. It introduces the theoretical background needed to answer the research questions. Section 3.1 summarizes the basic information about the project and outlines which data and assumptions were used. The methods of obtaining Valley-Charging simulation results are presented in section 3.2. Changes made in the MATLAB trolley-grid model are thoroughly described in section 3.3. Section 3.4 focuses on the theory behind the relationship of bus voltage and the available power capacity while section 3.5 studies how the position of the vehicle on the section affects its power demand. The effect of where the feeder cable is connected to the overhead line is explained in section 3.6. How the simulations deal with vehicles switching trolley-grid sections is outlined in section 3.7. Last section 3.8 focuses on brand new concept of I_σ and V_σ values that can help to predict what is going on on the section.

3.1. Introduction

This thesis can be described by two research questions:

Research Question 1
How can the already available bus measurements estimate the available power capacity in the trolley grid?

Research Question 2
How will estimator-supported Valley-Charging approach help to increase the penetration of IMC trolleybuses in terms of energy collected and limit violations?

The aim of the research is to provide in-depth analysis of available bus measurements, such as bus voltage, bus current or bus position, and to describe their potential for faster implementation of new technologies. Every trolleybus is measuring these values for the operational and safety purposes but their use remains far beyond beneficial. This part of the thesis can be called a theoretical research. At the end, it should show how valid the direction of the state of the trolleygrid estimation and the Valley-Charging approach is and what research directions should be taken to improve it. However, it turns into an applied research once the findings from RQ1 are applied at the Arnhem use case. It can come closer to the engineering aspect of the integration of new technologies as it can give insight into what is actually necessary for successful energy transition and public transport sector transformation. The results coming from the Valley-Charging approach IMC with the help of state of the trolley-grid estimator will be compared with best case scenario for which all the necessary information are known and with regular IMC charging scheme consisting of constant in-motion charging power and constant standstill charging power.

The mathematical models were developed in MathWorks MATLAB environment in the form of script. It contains the model of trolley-grid performing power flow calculations with voltage and current being of the highest interest. IMC on-board battery model has been added to capture the SoC of the vehicles.

3.1.1. Data

In order to perform simulations, input data were required. Most of them were prepared by the researchers from DCE&S department of TU Delft. It would namely be data describing the bus operation, such as bus velocities, bus power and bus position. Bus positions and the bus sections were made according to a real bus schedule with certain amount of randomization to also account for uncertainties in public transport, such as traffic jams or any other kinds of delays. Data describing the topology of trolley-grid sections like feeder cable placement or section length were used as well. Technical requirements and parameters, such as battery charging and discharging efficiencies, the efficiency of regenerative braking or voltage and current limits of a trolley-grid comes from the literature review. Their overview can be found in table 3.1.

Table 3.1: Technical parameters used for simulations

Battery round trip efficiency	η_{battery}	0.95 [-]
Regenerative braking efficiency	η_{regen}	0.9 [-]
Line Voltage limit	V_{lim}	490 [V]
Average overhead line current	I_{lim}	840 [A]
Allowed transmission losses	$\%P_{\text{loss}}$	10 [%]

On top of these, some data sets had to be created. These were the data which necessity followed from the research work for the purposes of simulations. The initial bus profile data only contained regular trolleybuses, so they had to be extended for IMC trolleybuses. For IMC operation outside the Arnhem trolley-grid, there are no data available. Value of 0 was chosen for all data sets to indicate autonomous operation where the on-board battery has to be discharged.

Result data come from experiments and simulations of the trolley-grid which make them primary data. That is especially the data regarding one-day SoC, power exchange between the grid, the motor and the battery or the energy picked-up by the battery from the overhead lines.

3.1.2. Assumptions

Narrowing down the topic for the purpose of this Master thesis required certain research and simulation assumptions.

Firstly, all the simulations of trolley-grid performed within this thesis use unilateral sections meaning that sections can only be fed from one substation and only has one feed-in point. Regular trolley-grids make use of bilateral connections. With the change of simulation logic which will be described in section 3.3 where more trolleybuses are co-simulated at the same time, this would cause extreme prolongation of running time. On the other hand, it can be said that bilateral grids are generally more stable with less severe voltage drops. If the results are favorable for the unilateral connection, it can be said they can work for bilateral connection, too.

Knowing the position of the vehicle on the route is a very crucial aspect of estimator. It enables determining parameters like substation nominal voltage, feeder cable placement or exact position of the trolleybus on a section. It is then assumed that the vehicles is equipped with a GPS location device and the simulation will use these data as input.

3.2. Valley-Charging Approach

The idea of Valley-Charging approach has already been addressed in sections 1.5 and 2.4. The main point of this thesis is the Valley-Charging scheme supported by the state of the trolleygrid estimator. The concept of the estimator was also explained in section 1.5. This scenario will use the estimator to predict the available power capacity the substation can provide at the time to optimize the charging power. To assess the accuracy of the estimator Valley-Charging scheme, another scenario called "Best Case" is also presented. It expects sensor installation and perfect communication during the operation not only between the vehicles on the grid but also between vehicles and substations. In other words, this scenario has all the information necessary to maximize the battery charging power and not breaking any limits at the same time. This scenario can serve as a benchmark for the Valley-Charging supported by the estimator. The following is a description of the Valley-Charging modelling.

3.2.1. Valley-Charging with communication

Having all the information about behavior of other vehicles on the grid, about the electrical parameters of section coming from real-time measurements and about substation limits enables the vehicle to use the full potential of the trolley-grid while not braking any limits of the grid. Nowadays, this kind of communication does not exist in trolley-grids as it would require massive investments in the infrastructure and the vehicle technology. It surely is a promising direction which the trolley-grid operators will take. For this thesis and the scenario called Best Case serving as a benchmark for the estimator supported Valley-Charging, historical measurement data were used to give the IMC bus an overview of the grid.

The key parameter is the unused substation power capacity. All the substation, with an exception of the one feeding the Centraal Station in Arnhem, can provide 800 [kW]. If the regular trolleybus operation and its demand is taken into account, this capacity is reduced. The rest is left for further load, in this case the IMC traction and on-board battery charging power. To maximize it, the value of what the substation can provide at every time of the day is crucial. It does not have to be the case that one substation feeds only one section. The substation usually services more of them. Table 3.2 shows what sections are fed by the same substation.

Table 3.2: List of substations and the sections they feed in Arnhem

Substation number	Section number
1	2, 3, 4
2	14, 15, 16
3	11, 12, 36
4	5, 6, 8
5	17, 18, 35
6	9, 32
7	20, 21
8	13, 19
9	25
10	22
11	30, 31
12	23, 24
13	28, 29
14	26, 27, 41
15	33, 34
16	42, 43
17	39, 40
18	44, 45
19	46, 47
20	48, 49
21	37, 38

Initial case of Arnhem trolley-grid with just trolleybuses was simulated for every day of the year to get total power demand of every section. According to table 3.2, total power demand per substation P_{subX} was determined by summing up power demand of each section related. It has already been mentioned that the substation can provide 800 [kW] of power at any time. To determine the power capacity left for battery charging $\Psi_{\mathrm{max,t}}$ and additional load at time t, the total substation power demand $P_{\mathrm{subX,t}}$, including the traction power of all the trolleybuses supplied by this substation and corresponding transmission losses, was subtracted from the substation power limit of 800 [kW]:

$$\Psi_{\mathrm{max,t}} = 800 - P_{\mathrm{subX,t}} \tag{3.1}$$

In order to get the data of $P_{\mathrm{subX,t}}$, the trolley-grid simulations with just the regular trolleybuses had to be performed to come up with the initial and already existing power demand the substations have to cover. $\Psi_{\mathrm{max,t}}$ now represents the total power still available for the new IMC trolleybuses. From their perspective, it needs be enough for both the traction and battery charging power. A look-up table was made out of these values for every single day of the year and for every single substation. Just like this, the perfect communication between the vehicle and the infrastructure is simulated and the IMC vehicles have a perfect information on what charging power it can achieve not to break the substation power limit. However, this value cannot be fully used by all the vehicles in case of multiple vehicles on one section. They need to make sure to share this available capacity. With the assumption of communication between the vehicles, the IMC vehicles know about other IMC vehicles connected on the same section or on a section that shares the same substation. This leaves the model with a sum of the vehicles eligible for battery charging power which is used to divide the available power capacity between the IMC vehicles equally. The final value is Ψ_{allowed} and means the maximal charging power in-motion.

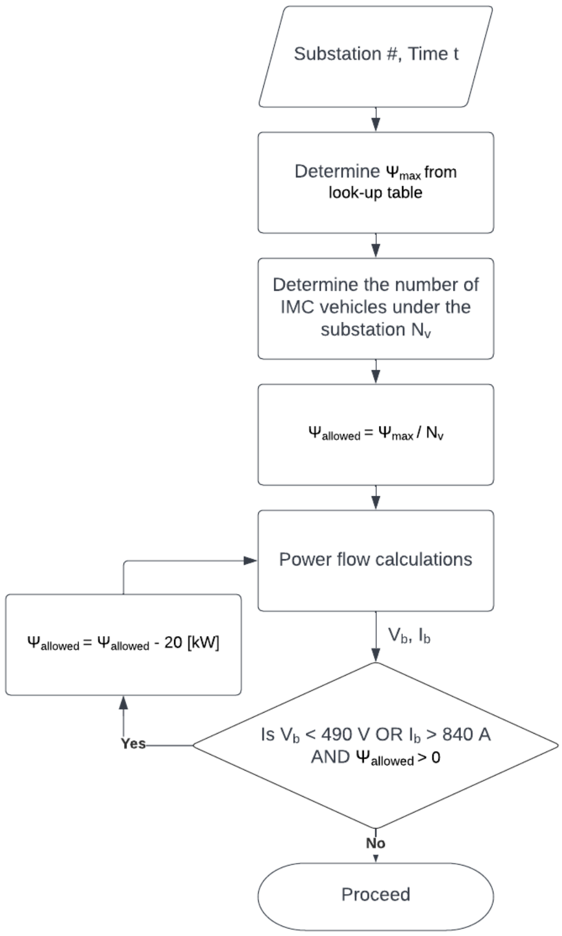


Figure 3.1: Process diagram of Valley-Charging approach with communication

Ψ_{allowed} serves as an input to the charging model which process diagram is shown in figure 3.2. Once the final charging power of either Ψ or Π is determined, the simulation goes on to perform the power flow calculations with values of current and voltage as a result. The power flow calculation needs to be performed as the value of Ψ_{allowed} states what is the maximal power the newly added IMC trolleybus can draw, but it does not tell if it is also feasible in terms of the line voltage limit and overhead line current limit. At the end, the model checks whether such charging power that was used does not brake any limits of voltage or current. If so, the loop goes back to take another iteration with reduced charging power by 20 [kW]. Doing this charging power reduction, the model can at the end decide to charge very low power or even 0 [kW] as under some conditions just the power demand for traction might cause problems. Once 0 [kW] charging power is reached, the charging process continues.

3.2.2. Valley-Charging with estimator

Second Valley-Charging approach for IMC trolleybuses is using the state of the grid estimator. It can be described as a set of rules and conditions that suggests the optimal battery charging power. Unlike the previous charging concept, it works with limited information that can be received either via on-board measurements or GPS location. This set is the essence of the first research question RQ1 which will be the topic of chapter 4. It is a necessary tool for running the simulations for the Arnhem case study. This section will therefore not deal with the decision tree of the estimator that sets the charging power but how the estimator is built into the trolley-grid model in MATLAB.

The previously described approach could use iterative process to decide on the optimal charging power for both the IMC vehicle and the trolley-grid. The estimator approach should reflect realistic operation much more. That is why the estimator gets only one opportunity to evaluate the equations, conditions and historical experience and set the most ideal charging power. The requirements of the battery management system of the vehicle as well as the physical limitations of the trolley-grid have to be included in the decision making process already. This is very different from the other approach which looked at the correctness of the suggested charging power at the very end of the process after the simulation ended and potentially got another try.

The ”Best Case” scenario charging approach works with per-second change of charging power. However, the estimator should avoid such quick change of conditions. It is not a matter of the on-board power electronics not being suitable, it is the matter of power balance of the trolley-grid. Thus, the charging power is kept constant for 3 [s]. This value has been chosen because it is a compromise between the update time not being too long and also after 3 [s], the measurements of voltage and current, such as their derivatives, can be more informative. In the meantime, the measurements and other available information are being evaluated to prepare the decision for the next estimator iteration. Within the MATLAB model, this is solved by a counter, which increases its value every simulation second. Its initial value is 0. This means that the estimator code is skipped until the counter reaches 3.

3.3. Model Description

To simulate the DC trolley-grid, a model has been created by TU Delft researchers. After specifying the desired section and type of section connection (unilateral/bilateral), a one day operation on the section is performed. This allows the user to obtain results of power flow between the substation and the connected vehicles as well as bus current and bus voltage for each vehicle. It can be used to simulate any DC trolley-grid if adequate input data are used. For further description of the basic model and the assumptions used, the model has been thoroughly introduced in [13].

The model also takes the seasonal change of weather into account. It affects the amount of HVAC power to be supplied. In previous research work at DCE&S at TU Delft, a model of such trolleybus HVAC system has been developed. It considers heat flows through the walls and windows of the vehicle, natural air and heat transfer while the door are open for passengers to get off as well as heat produced by the passengers themselves. These power data were included in the total bus power demand.

Bus point-of-view

For the purposes of this thesis, the model had to be considerably adjusted. The part of the model calculating the electrical properties, such as voltage and current, has been left unchanged, but the logic of the simulation had to be redone. Initially, the model was section-oriented. That means, it could only simulate one section at a time, knowing only the traffic and results happening on that particular section for one day. This was especially unsuitable when the objective of the simulations was to follow bus whole-day operation. On top of that, the scope of observable quantities had to be extended by, for instance, bus SoC. It requires chronological bus simulation to record what the SoC was at time [t-1] to be able to update the level for time [t]. Thus, the logic of the model has been changed to bus-oriented. Instead of specifying the section to be simulated, bus numbers are required for the start of the simulation. It follows a bus-by-bus per-second simulation from the beginning till the end of their operation while the traffic of other buses is still taken into account.

It is fairly possible that the buses specified for the simulations meet on the same section.

Specified bus numbers	[1 2 3 4 5]
Buses meeting on one section	[1 4]

According to the altered logic, the model would firstly simulate bus 1 under corresponding conditions, which includes the presence of bus 4 also. When the model wants to then simulate bus 4, the simulation would be identical to the one of bus 1. The model now takes data about bus 4 during the initial simulation already into account and the bus is skipped afterwards. This has been adopted to save the simulation time. To make this workaround function, the information on how many IMC trolleybuses are connected to the same section had to be determined at the beginning of every time step. Array signaling appropriate IMC vehicles on the same section was created which then served as a basis for skipping the lengthy power flow calculations. To present an example, let's assume the 9 IMC vehicles are placed on section like shown here:

IMC Trolleybus	40	41	42	43	44	45	46	47	48
Section	2	0	0	38	0	38	0	0	0

The final array would put together IMC vehicles 43 and 45 and then all the vehicles with section 0 suggesting these vehicles still have not started their operation or they are outside the trolley-grid in autonomous mode. The array would look like this:

IMC Trolleybus	40	41	42	43	44	45	46	47	48
Co-simulation	0	1	1	2	1	2	1	1	1

Zero value represents operation alone on the section for bus 40. Number 1 joins all the vehicles on "section 0" and number 2 would be useful for simulating section 38 with vehicles 43 and 45 just once. The model would pick vehicle 43 (after simulating 40, 41 and 42) and go on to simulate section 38 at the particular time step. As it already includes vehicle 45, once it is bus 45 turn, the model detects that its battery power value has already been filled in and skips the power flow calculation. It then figures out the common number representing the co-simulation, in this case 2, to copy data such as total power demand which have been stored only for trolleybus 43 in the initial power flow calculation.

When the logic of the trolley-grid model was section-oriented, it only cared about final data of maximal current in the overhead lines, minimal section line voltage and the total power demand of the section. These variables are more or less global for the section as a whole. By creating bus-oriented model, the urgency of following buses' particular behavior on the section made it necessary to keep track of the voltage and current at the point of connection of the current collector and the overhead line. Previously, the model did not care which buses were currently being simulated. If on section 2 there would be buses 2, 4 and 12, the initial section-oriented model would still label them 1, 2 and 3 by the total amount of vehicles simulated. In order to be able to store their values of current and voltage after the power flow calculation is done, indexing of the vehicles is necessary. Just like this, every vehicle being currently simulated gets an index of the position in the result arrays which are then used to reach those values and store them. First of all, an array of bus numbers connected to the same section is created. These are the trolleybuses that are going to be simulated. Using the trolleybus numbers already mentioned in this paragraph, the array would be:

$$Nr = [2 \quad 4 \quad 12]$$

Firs step is to determine position of each bus in Nr array. For array Nr, this would be:

Position2	Position4	Position12
1	2	3

The array which the model uses to determine the order of the buses in the result arrays is created based on the position of the vehicles from the substation feeder cable. This array has always one more element than the array *Nr*, in this case 4 elements, accounting for the feeder cable connection with the overhead lines. It always gets the highest number. Assuming the trolleybus 12 is on one side of the section from the feeder cable and vehicle 2 and 4 being on the other one, the array would like this:

$$Nodes = [Position12 \quad Feeder \quad Position2 \quad Position4]$$

$$Nodes = [3 \quad 4 \quad 1 \quad 2]$$

All the arrays of voltage and current will be sorted this way. To get data of one specific trolleybus, index of the position of each bus in the *Nodes* array has to be figured out:

Index2	Index4	Index12
3	4	1

Direction

For a latter feature of the estimator, it is crucial to know in what direction the IMC vehicle moves. Whether it is towards the Arnhem Centraal (A) station or from the station. In generic terms, if the direction is from autonomous mode to trolley-grid or the other way round. As there are two directions, in order to distinguish between them, binary values of 1 and 0 were used. The A station is exclusively covered by section 38. If the trolleybus sets off from there, the following section it will enter is section 37. If two consecutive time steps see sections 38 and 37, the direction towards the exit from the trolley-grid is denoted:

$$IFBussections(t-1, bus) == 38 \quad \&\& \quad Bussections(t, bus) == 37 \rightarrow Direction = 0$$

On the other side, the first section the trolleybus enters in Arnhem on its way to A station is 24. As it was outside of the grid in autonomous mode, its preceding section number was 0. Similar condition then applies:

$$IFBussections(t-1, bus) == 0 \quad \&\& \quad Bussections(t, bus) == 24 \rightarrow Direction = 1$$

Battery Charging

The initial model could only work with conventional trolleybuses. To also include IMC operation, charging and discharging of IMC on-board battery had to be implemented. Figure 3.2 shows the process diagram of IMC. Data of bus velocity v, maximal allowed charging power in-motion Ψ_{allowed}, standstill charging power Π and bus power demand P_{bus} serve as the input. Based on these, decision on the charging power is made. The value of Ψ_{allowed} is the total power capacity left for IMC and comes as an output of the trolley-grid estimator. Firstly, the bus velocity is taken into account. Due to the thermal effects on the point connection of overhead lines and the current collector, the bus should only maximally draw charging power Π which is lower than Ψ. When standstill, only constant charging power Π was considered when using the estimator. As the traction power is 0 [kW] and the trolleybus can only demand HVAC power, there should be capacity for Π. Valley-Charging scenario with communication could curtail even the standstill charging power. When the bus is moving, Ψ_{allowed} is considered. The trolleybus needs to make sure that the charging power is within the technical limits of the battery and is thus capped at 240 [kW]. Next decision branch deals with the bus power P_{bus}. Two situations can occur; either the bus is drawing power for traction purposes, $P_{\text{bus}} > 0$ or the bus is braking, $P_{\text{bus}} < 0$. In the case of the first one, the sum of the battery charging power and the power demand of the motor cannot go beyond the total power limit of the current collectors and bus electronics of 500 [kW]. In the latter case, the bus is braking and can regenerate the kinetic energy and store it in its on-board battery. At the same time, there is the opportunity to also charge the battery from the overhead line. However, the battery can only accept 240 [kW]. The regenerative braking energy has higher priority over drawing power from the grid and if the combination of the two powers is higher, the charging power from the grid is adjusted accordingly.

The process described above is used to determine the power used to charge the IMC on-board battery. The parameter, that proves the capability of whole day operation and has to be recorded, is the SoC.

During the IMC mode, both the overhead lines and regenerative braking could contribute to charging. Their sum is then transformed into SoC by following equation:

$$\Delta SoC = \frac{P_{\text{bat}} \cdot t \cdot \eta_{\text{charge}}}{3.6 \cdot 10^6 \cdot E_{\text{bat,max}}} \tag{3.2}$$

ΔSoC .... Per-second difference of SoC [kWh]
P_{bat} ..... IMC on-board battery charging power (sum of charging and regenerative braking power) [W]
t .... Time [s]
η_{charge} .... Battery charging efficiency [-]
$E_{\text{bat,max}}$ .... Total energy capacity of IMC on-board battery [kWh]

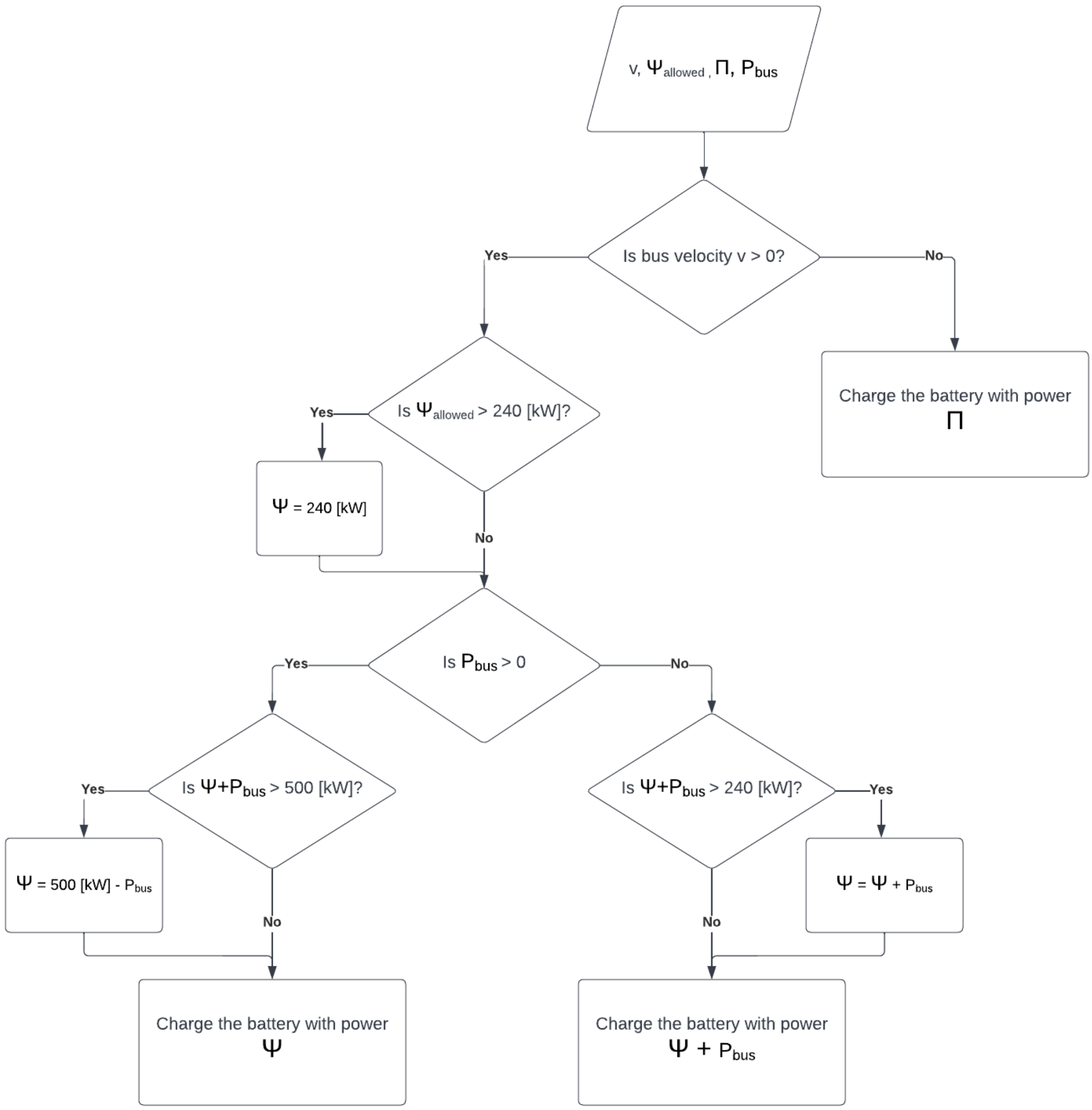


Figure 3.2: Process diagram of IMC battery charging

The battery charging power is multiplied by the time (which for a per-second difference is always $t = 1$) and efficiency of energy conversion and divided by the total energy capacity. The number is then converted to [kWh]. The final level of SoC is then calculated by adding the ΔSoC to a SoC at time (t-1):

$$SoC(t) = SoC(t-1) + \Delta SoC \tag{3.3}$$

When the simulation is started, the initial SoC of the on-board battery has to be specified. In the case study of Arnhem, there are two options where the IMC trolleybus can start its journey. It is either at Arnhem Centraal (A) where the trolleybus starts with the current collector connected to the overhead line and can start charging the battery right away or at Wageningen (W) which is a stop outside the Arnhem trolley-grid and the vehicle has to start in battery mode. If the initial SoC is set to be 100%, the first journey from A to the moment when the IMC trolleybus exits the trolley-grid is pointless as the battery cannot be charged more. On the other hand, any low initial value would make the journey from W to the Arnhem trolley-grid inoperable. An initial SoC of 60% has been used for both starting points of the simulations. For the firstly mentioned, it gives the opportunity to utilize the overhead lines even during the first ride. For the latter one, an assumption has been made that technically the vehicle starts its journey with 100% from W and when it enters the Arnhem trolley-grid it has 60% SoC also.

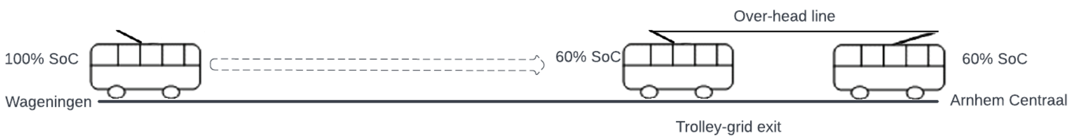


Figure 3.3: Illustration of initial State of Charge (SoC) choice

Battery discharging

Different approach for determining the ΔSoC has to be chosen while in the autonomous mode outside of the trolley-grid. The battery is mainly used for traction purposes and is being discharged. On the other hand, it can still accept energy from regenerative braking. Real operation measured data were available for the IMC operation under the overhead lines. This made battery charging from overhead lines and from recuperation very accurate. For autonomous mode, there were no bus measurement data made. The amount of energy needed for traction and also the energy that can be recovered had to be determined by an analysis of the autonomous part of the route. The line 352 goes from Arnhem Centraal (A) to Wageningen (W). From A, there are overhead lines going in the W direction. The last bus stop before leaving the trolley-grid is Arnhem, Gemeentehuis. From this point on, both the distance of the autonomous section and the time necessary to cover the distance were found out. One-way trip takes 14.4 [km]. According to the timetable for year 2022, the one-way trip takes from 18 to 26 [min] based on the time of the day and the corresponding traffic situation. For the purposes of this calculation, the most occurring time was chosen to work with.

One-way distance autonomous mode	One-way trip time average
14.4 [km]	24:12 [mm:ss]

With these two values, the distance travelled per second could be calculated based on the values for an autonomous round trip:

$$d = \frac{(14.4 \cdot 2)}{24.2 \cdot 2 \cdot 60} = 0.0099 \quad [km/s]$$

The energy consumption of the IMC bus can be divided into two parts. The first part accounts for the traction purposes and the second one represents the auxiliary demand, such as Heating, ventilation and air conditioning (HVAC), lighting or minor electronic devices on-board. A value of 1.5 [kWh/km] traction energy consumption $E_{\mathrm{tr,km}}$ was used as it is the commonly used value in the literature. However, this value does not include the possible regenerative braking energy. Previous research has shown that approximately 30% of the total energy demand can be recuperated, which leaves the total energy consumption at 70% of the initial 1.5 [kWh/km]. The energy consumption of auxiliaries was figured out based on real measured data of regular trolleybuses, specifically the auxiliary power demand and bus velocity. Using these data does not distort the result of the model as the auxiliary energy consumption is insignificantly dependant on the route type and varies more based on the seasonal weather change due to HVAC being the major contributor. For each day of the year, following calculations were performed:

$$E_{\text{aux,tot}} = \sum_{\text{t}=1}^{T} P_{\text{aux,t}} \cdot (t = 1) \tag{3.4}$$

$$d_{\text{tot}} = \int v \, dt \tag{3.5}$$

$$E_{\text{aux,km}} = \frac{E_{\text{aux,tot}}}{d_{\text{tot}}} \tag{3.6}$$

$E_{\text{aux,tot}}$ .... Total energy demand from auxiliaries during one day [kWh]
P_{aux} .... Power demand of auxiliaries [kW]
d_{tot} .... Total distance covered during one day [km]
$E_{\text{aux,km}}$ .... Energy consumption by auxiliaries [kWh/km]

To simulate the discharging process during autonomous operation, two vectors were created in MATLAB containing traction and auxiliary energy consumption for each day of the year. The model then picks the right values of energy consumption based on the currently simulated day of the year.

Table 3.3: Example of energy consumption input data. Second column includes energy consumption of traction motor, third column energy consumption of HVAC

Day of the year	$E_{\text{tr,km}}[kWh/km]$	$E_{\text{aux,km}}[kWh/km]$
04.12.2020	1,05	1,26
05.12.2020	1,05	1,40
06.12.2020	1,05	1,52
07.12.2020	1,05	1,49
08.12.2020	1,05	1,22
09.12.2020	1,05	1,39
10.12.2020	1,05	1,15

The derivative of SoC, ΔSoC, is calculated as follows with a safety factor of 1.2 representing unexpected situations like changing of directions or very high traffic. The total SoC is determined by subtraction of this change:

$$\Delta SoC = \frac{1.2d \cdot (0.7E_{\text{tr,km}} + E_{\text{aux,km}})}{E_{\text{bat,max}}} \tag{3.7}$$

$$SoC(t) = SoC(t-1) - \Delta SoC \tag{3.8}$$

Final data

Previously when the public transport operation on a single section was simulated, the data of power demand, current and voltage were complete as every single time of the day was captured in this section data. With the bus oriented simulation approach presented in this chapter, data are collected from bus point of view and section data would be left incomplete as only times when the IMC vehicle is connected to a section are simulated. Such situation is illustrated in following table.

Time	1	2	3	4	5	6
Vehicles connected	[1]	[1]	[1]	[1, IMC]	[1, IMC]	[1, IMC]
Section power demand data trolleybus 1 only [kW]	75	80	60	100	90	110
Section power demand data from IMC POV [kW]	0	0	0	240	220	215
Final power demand data for section [kW]	75	80	60	240	220	215

Having a random section, there is only one regular trolleybus 1 connected at time 1-3. At 4, an IMC vehicle enters the section also. If the initial trolleybus only operation is considered (only trolleybus 1 connected) and a section-oriented simulation logic would still be in use, the results of total power demand would look like in row 3. However, the logic of simulation was changed so now it follows the IMC vehicle. The section data of total power demand would then miss information from time 1-3, even though there was a vehicle connected (row 4). To be able to provide final result data from both POVs, the data has to be merged. The simulation of trolleybus only operation was performed for every day of the year and the result data were stored (row 3). After the simulation of IMC operation, the values from row 4 colored red replace the values from row 3 colored yellow to create final data set of total power demand of the section, shown in row 5.

This way of data merging is not only done for power demand data but also for data of current and voltage. The data of current and voltage are relevant for one section; the operation on one section does not affect the values of voltage drop and magnitude of current on the other (assumption of unilateral connection). This is not the case of the power demand which is not relevant for a section but for a substation. As there are usually more sections being fed by the same substation, determining the fraction of total power demand on the substation by one section is not enough and power demand from other relevant sections have to be added. The list of substations and their sections which have also been used to coming up with the final power demand data is presented in table 3.2.

During the power flow calculation, a value of battery charging power is stored as P_{bat}. It is a combination of what the IMC trolleybus draws from the trolley-grid $P_{\text{ch,grid}}$ as well as what the battery can accept from regenerative braking, P_{reg}:

$$P_{\text{bat}} = P_{\text{ch,grid}} + P_{\text{reg}} \tag{3.9}$$

Both of these quantities can have non-zero and zero values, independently. Apart from the SoC of the batteries, the amount of energy collected E_{col} is also a great factor to assess how successful the charging of the battery was.

$$E_{\text{col}} = \frac{\sum_{\text{T}=1}^{75600} P_{\text{bat}}}{3,6 \cdot 10^6} \tag{3.10}$$

To keep track of the success rate of every version of the simulation scenario, either the Valley-Charging scenario with communication or the one with estimator, the amount of optimization failures have to be monitored. Specifically, limits of power demand, current and voltage were of interest. At the end of every power flow calculation, 3 conditions, each applicable to one quantity were placed. They checked if any limitation was violated. If so, the model stepped into the condition and increased the number of counter by 1.

3.4. Relationship of bus voltage and available power capacity

The state of the trolley-grid estimator can only use information that can be measured on-board or that can be figured out based on the GPS location of the vehicle. One of these measurable quantities is the bus voltage. For the most accurate function of the estimator, the information of Ψ_{max} presented in section 3.2 would be valued the most but it is exactly the parameter that cannot be measured on-board. Nevertheless, it seems there is a relationship between the bus voltage and the available power capacity for IMC battery charging the substation can provide. An example of the relation can be found in figure 3.4. That can be described as when the bus voltage is close to the nominal voltage of the substation, there does not have to be other vehicles demanding power supply from the substation and dragging the voltage down. Then, there is a chance of having high availability of power for battery charging. On the contrary, when there is a considerable voltage drop, it is likely there are other vehicles drawing power and the charging power should be adjusted. However, this reasoning is not always 100% true as can be seen from the example plot. Other circumstances can also influence the voltage drop such as vehicles braking. That is why there might be rather low capacity available even though the voltage of the vehicle is at the nominal value of the substation. For this reason, a probabilistic analysis of the historical measured data had to be done to advance the decision process of the estimator. The desirable function should be:

$$\Psi_{\max} = f(V_b) \tag{3.11}$$

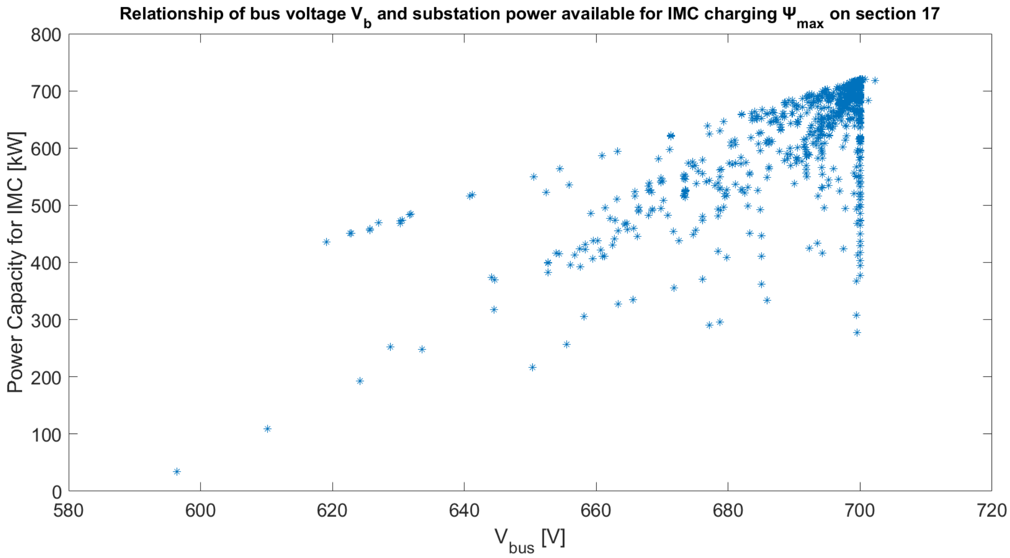


Figure 3.4: Relationship of bus voltage V_b and substation power available for IMC battery charging $\Psi_{\max}$. Data from Arnhem trolley-grid section 17. Substation nominal voltage $V_s = 700[V]$. Voltage above 700 [V] is a matter of vehicles braking. Day 1.4.2020

The area of the plot had to be divided into certain sections for which the probability has been calculated. The y-axis of power capacity for IMC will use steps of 10 [kW]. If the state of the grid estimator suggests a charging power value, it will be rounded to the closest power capacity value from this analysis. With regards to the bus voltage, a step of 1 [V] was kept. It is usual that the voltage measurements have a decimal place. In this case, the number is rounded down. Also, the relevant intervals of the analysis were made 0 - 800 [kW] for the power capacity (the maximal value of power capacity for IMC is only 720 [kW] as 10% was deducted to account for transmission losses) and 490 - 740 [V], where 490 [V] is the lowest voltage limit the overhead lines are still capable of operation. The upper limit is a matter of braking voltage.

To demonstrate the process of probabilistic analysis of the relationship, figure 3.5 will be used. It shows an illustration of a cone similar to the real-data one from figure 3.4. It reflects the relationship of V_b and $\Psi_{\max}$ on certain section, where the IMC bus currently is. Each star determines one data point of historical data. Let's consider that the measured bus voltage is V_b. The idea of the analysis is to tell what is the probability of having an available power capacity for battery charging of at least $\Psi_{\max}$ for this V_b. Such information tells the IMC vehicle how sure it can be to request this charging power from the substation. The area for which the probability is calculated is firstly determined by the constant lines of $\Psi_{\max}$ and V_b. Mainly, there is a vertical restriction from the side of voltage. The calculation needs to make sure that the bus voltage varies in time based on the current situation on the trolley-grid section. For this reason, a range of bus voltages has to be assumed instead of a single value. Considering the fact that the estimator updates its suggested charging power every 3 [s], the derivative of voltage $\frac{dV_b}{dt}$ had to be investigated. The boxplot in figure 3.6 shows statistical analysis of the trolleybus voltage derivative. Historical measurement data gathered from real trolleybus operation in Arnhem trolley-grid were taken. The data set was created by just taking the values of bus voltage when the bus velocity was higher than 0. Negative values of $\frac{dV_b}{dt}$ represent the bus voltage going down, whereas the positive values show the voltage increasing. It can be seen that the middle value, median, represented by the red horizontal line is very close to 0 [V]. 25. and 75. percentile marked by the black horizontal lines are around 2 [V/s] and -3 [V/s], respectively. In statistics, the percentile of 95 is an acceptable value to be used in calculations. In other words, a value of $(\frac{dV_b}{dt})_{95\%}$ means that only 5% of values are higher. Following value meets the condition:

$$(\frac{dV_b}{dt})_{95\%} = -11,66 \quad [V/s]$$

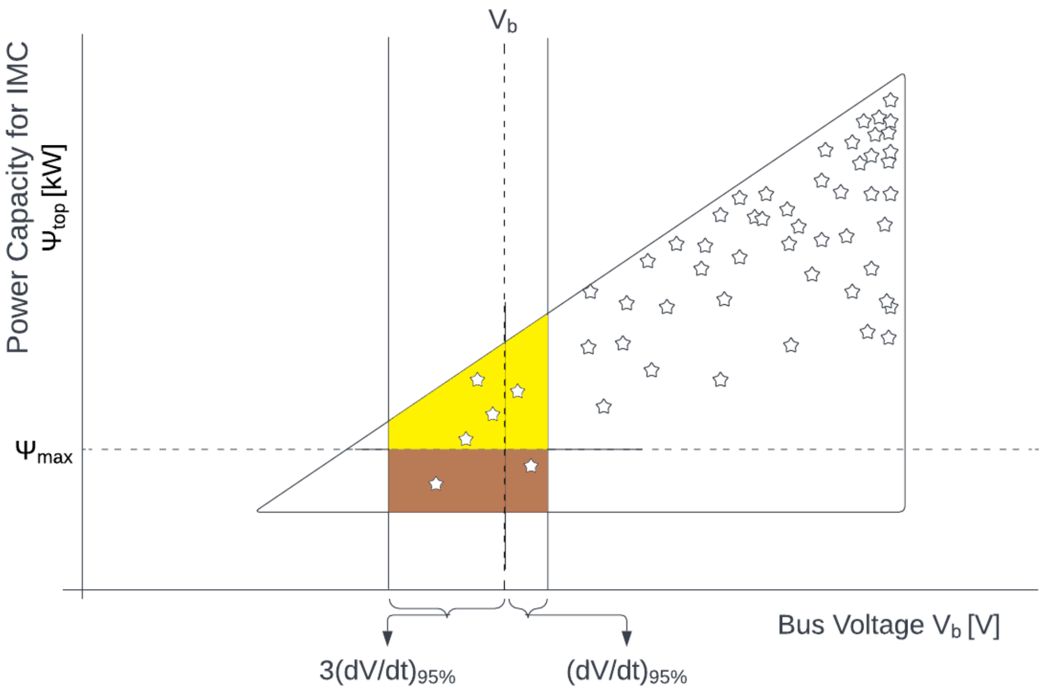


Figure 3.5: Illustration of probability calculation for the relationship of bus voltage V_b and substation power available for IMC battery charging Ψ_{max}. Yellow area represents power capacities larger than Ψ_{max}. Brown are represents power capacities lower than Ψ_{max}

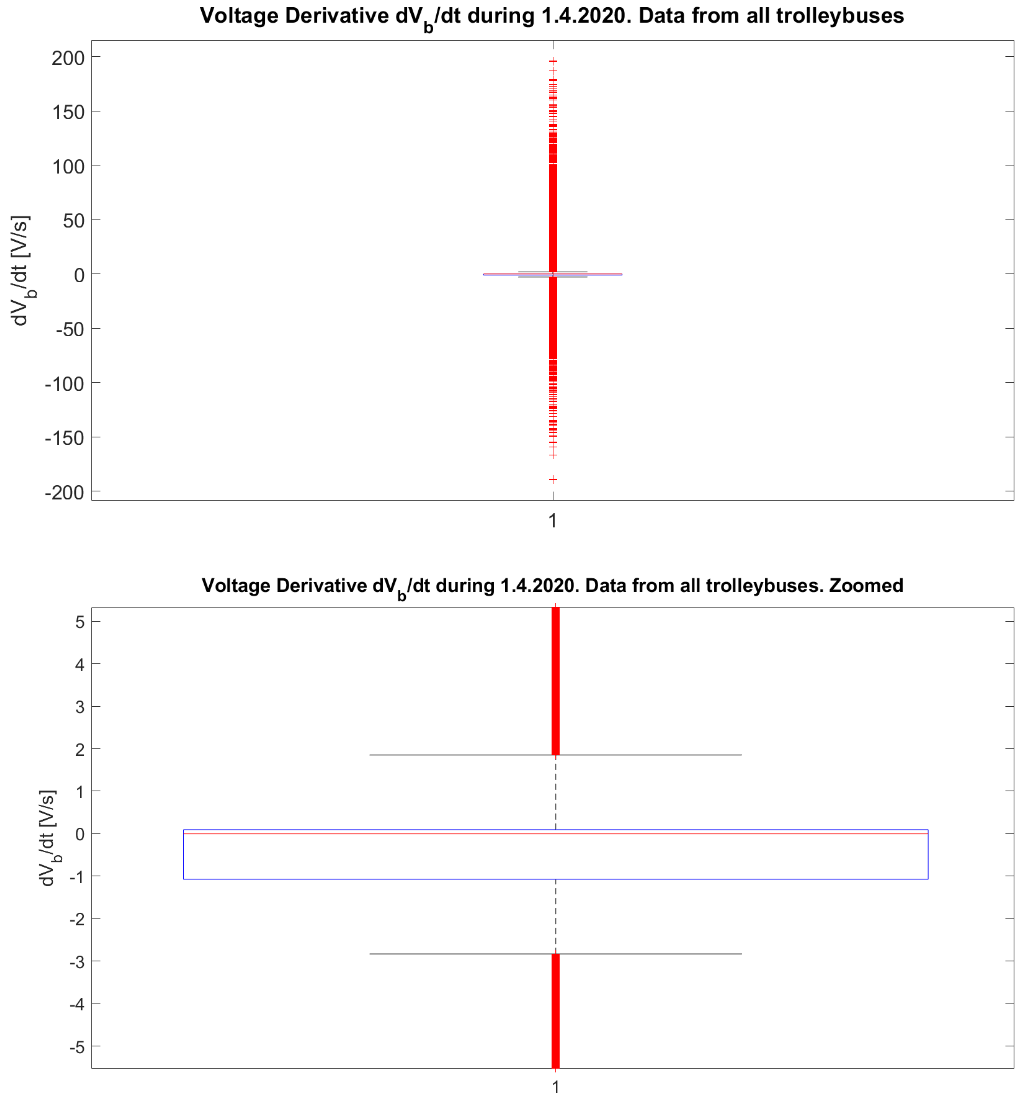


Figure 3.6: Statistical analysis of bus voltage derivative dV/dt from 1.4.2020. All trolleybuses from Arnhem grid. Upper figure shows the whole boxplot even with the outlier points. Bottom figure zooms to the statistical box to show the 25 and 75 percentile and the median

To determine the value of -11.66 [V/s], only negative values of voltage derivative were considered. The reason is that the decrease of voltage is much more important to account for compared to a voltage increase. In case of voltage increase, it is more likely that the power capacity available will be higher, which is also evident from figure 3.5. The voltage range takes $3(\frac{dV_\text{b}}{dt})_{95\%}$ down and $(\frac{dV_\text{b}}{dt})_{95\%}$ up. Factor of 3 was chosen based on the frequency of updating the estimator, which is every 3 [s]. In total, 35 [V] will be used as $3(\frac{dV_\text{b}}{dt})$ and 12 [V] as $(\frac{dV_\text{b}}{dt})$.

Horizontally, there are no boundaries. The area is just divided by the horizontal constant line which is set by a particular Ψ_max. The yellow area contains all the data points that in the voltage range had available power capacity of at least Ψ_max. The brown region recorded power capacity lower than Ψ_max.

Within the voltage range, there are 6 data points in total, 4 of them in the yellow area and 2 in the brown area. The probability of having at least Ψ_max available is then computed by dividing the number of data points above the horizontal line by the total amount of data points within the voltage range:

$$p_{\Psi_\text{max}} = \frac{N_\text{yellow}}{N_\text{total}} = \frac{4}{6} \approx 0.66 \quad [-] \tag{3.12}$$

The same process is repeated for every combination of V_b and Ψ_max resulting in a look-up table of probabilities. Separate look-up tables had to created for each section. During simulations, the bus voltage is determined by power flow calculations and used as a V_b to find the correct probability. A chunk of such table is shown in figure 3.7 as an example. The actual look-up table is 750x720 (voltage x power) per one section.

		Power Capacity for IMC [kW]					
		490	**500**	**510**	**520**	**530**	**540**
Bus Voltage [V]	**681**	0,459	0,459	0,297	0,216	0,108	0,108
	682	0,774	0,736	0,396	0,075	0,038	0,038
	683	0,826	0,803	0,601	0,225	0,062	0,062
	684	0,889	0,876	0,755	0,422	0,225	0,225
	685	0,915	0,906	0,821	0,587	0,317	0,314
	686	0,919	0,911	0,830	0,608	0,351	0,333
	687	0,925	0,917	0,840	0,633	0,394	0,345
	688	0,899	0,892	0,826	0,662	0,473	0,386
	689	0,902	0,895	0,832	0,672	0,488	0,402

Figure 3.7: Example of a look-up table of probabilities based on the bus voltage V_b and available power capacity Ψ_max

During the simulations, the use of the look-up table starts by knowing the bus voltage which is measured on-board. Based on this value, a row of probabilities of the available power for charging related to the this particular bus voltage is acquired. When it comes to choosing what probability and thus which available power should the model work with, it needs to be sure that there is enough certainty to take such power from the grid. If only power capacity of 20% probability will be taken, the violation of trolley-grid limits is very likely. On the other hand, the model cannot go for a probability of 100% as this would result in unreasonably low charging powers and the whole-day operation would be put into jeopardy. For this reason, the estimator tries to find power capacities with at least 95% probability. This value originates in statistics and has already been discussed within this section. Such probability for this relationship was named Kappa K and the final relationship between the bus voltage and the available power capacity is:

$$\Psi_\text{max} = f(V_\text{b}, \mathrm{K}) \tag{3.13}$$

3.5. IMC Bus Position

The position of the vehicle on a section plays a vital role. Special attention should be paid to the section length and the feeder cable placement. Together, they determine the maximal amount of voltage drop. If the section is long with a substation feeding it at the end, the trolleybus may end up in a position far away from the feeding point. When power of lower hundreds of [kW] is required, it results in a considerable voltage drop. This might be solved by putting the feed-in point to the middle of the section. However, this approach prevents the vehicles to sense the presence of other vehicles when on the opposite side of the feed-in point. This effect will be further discussed in section 3.6. The position of the vehicle on a section determines the maximal allowed bus power demand in order not to break any limits of the trolley-grid. It is the line voltage limit that makes the grid stable, current limit in the overhead line to prevent the cables from overheating and it is also the amount of transmission losses. All these limits come from the literature review and are presented in table 3.1.

What the IMC bus can, to some extent, control, is the amount of power drawn from the overhead lines. More specifically, it is the on-board battery charging power that is easier to control. Not charging the battery with maximal power does not affect the current operation under the overhead lines but may of course result in lack of energy during the autonomous mode. The traction power can be adjusted in case of power shortage too, but for the purposes of this thesis only battery charging power will be taken care of.

The maximal power demand allowed will definitely be different for alone operation when the trolleybus is the only vehicle connected to the section and for case when there are multiple vehicles on the section. The way of determining the cap value for one vehicle is easier as equations describing the situation pictured in figure 3.31. For multiple vehicles, calculation process gets more complex. Both approaches will be presented in following subsections.

3.5.1. One Vehicle

Transmission losses limit

Figure 3.8 shows the magnitude of voltage drop based on the position of the vehicle on a section. Each of the lines represents certain bus power demand in [kW]. It can be seen that the voltage can drop below the operational voltage limit of around 500 [V] for the charging powers higher than 400 [kW]. With the IMC500 technology, such extreme power demand may occur and its effect should be compensated for.

If the IMC vehicle decides to charge the battery, it is significantly increasing the power demand on the substation and thus also the related transmission losses. As the voltage drop from figure 3.8 can be translated into a power loss, the battery charging power demand can be curtailed according to the position of the vehicle on the section. By doing this, both the power transmission losses and the magnitude of the voltage drop will be reduced. It is assumed, that the transmission losses in the overhead lines should not exceed 10% of the bus power demand at no instant [4].

The maximum bus power demand to meet that criterion was determined analytically. Firstly, the GPS location of the bus gave the distance of the bus from the feed-in point and also the feeder cable length, which can be translated as the total resistance $R + R_f$. The concept of I_σ allows to calculate what the power transmission loss would be in case of only single bus connected to the section. These two values together represent the transmission power loss. In order to calculate the desired power demand which does not result in power loss higher than 10%, following equation had to be solved:

$$0,1 = \frac{(R + R_\mathrm{f}) \cdot I_\sigma^2}{(R + R_\mathrm{f}) \cdot I_\sigma^2 + P_\mathrm{cap}} \tag{3.14}$$

where the P_cap stands for the bus power demand cap and is the unknown in this equation. I_σ used the equation 3.34 which contains variable P_b that is for the sake of this calculation changed to P_cap. This current value could be used to determine the 10% bus power demand cap. However, the presence of other trolleybuses on that section would affect the voltage and current of the bus and thus might increase the transmission losses. Figure 3.9 shows a histogram of difference between the transmission

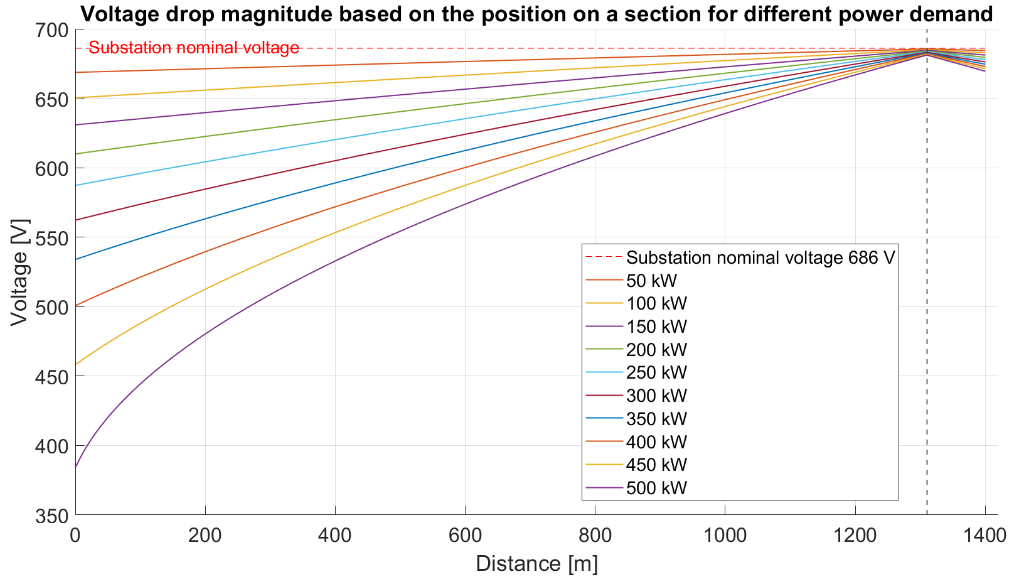


Figure 3.8: Voltage Drop magnitude based on the position on a section for different power demand. Nominal substation voltage 686 [V]. Vertical dashed line represents the feeder cable placement.

losses during regular trolleybus operation and transmission losses for single bus operation only. The data tell us that 99% of the cases this difference is lower than 20 [kW] and almost 98% is lower than 10 [kW]. It would therefore be reasonable to decrease the final power demand cap by 10 [kW] to account for the cases of multiple buses connected to one section. This can be done by following the difference between I_σ and actual bus current I_b. If there is any difference suggesting presence of another vehicle, 10 [kW] will be further deducted from P_cap

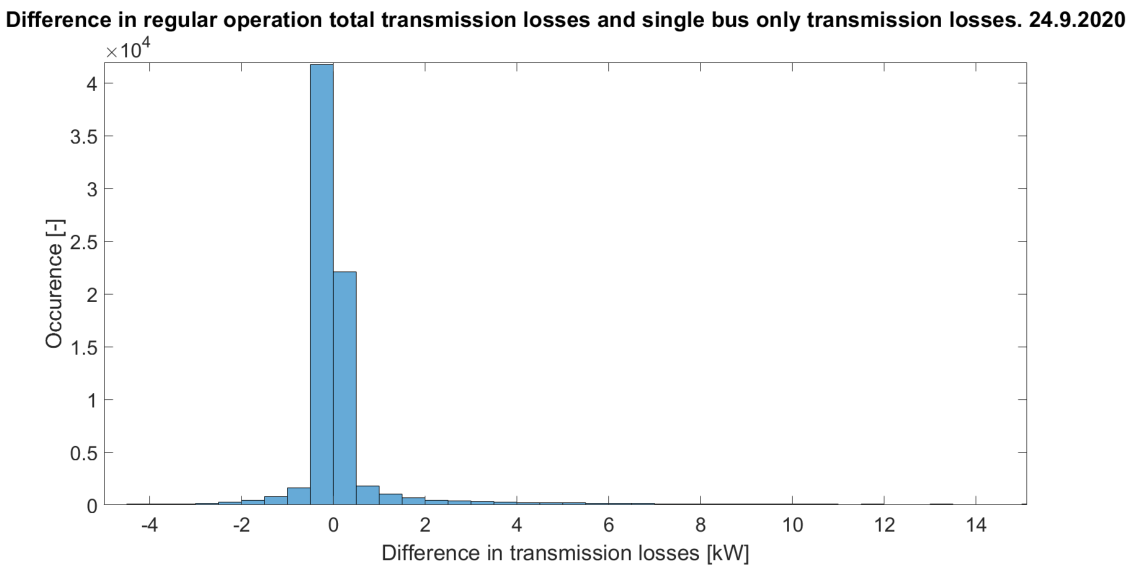


Figure 3.9: Difference in total transmission losses of regular operation and one-bus-only connected operation

Solving equation 3.14 for every section of Arnhem trolley-grid set the maximal power that can be drawn from the trolley-grid based on the distance of the vehicle from the substation feed-in point. The result has been used as a look-up table during the simulations. Power caps of few sections in Arnhem are plotted in figure 3.10. The plot is limited at the y-axis by the maximal power transfer between the overhead lines and the IMC bus of 500 [kW] and at the x-axis by the maximal distance of the vehicle and the feed-in point, which is 2750 [m] in Arnhem. The graph shows that in terms of power transmission losses IMC vehicles can draw the full possible 500 [kW] while close to the feed-in point. The reason, why the curves for each section differ and especially the distance for drawing the maximum power is no longer possible, is twofold. Firstly, it is the nominal substation voltage. The lower it is, the better conditions for regenerative braking are but the higher the losses. Secondly, it is caused by the length of the feeder cable going from the substation to the feed-in point of the section. The longer the cable, the higher the resistance which ends in higher voltage drop and higher transmission losses. Table 3.4 sums up these two parameters for the sections plotted in figure 3.10. It is evident why section 36 with the lowest nominal substation voltage and the longest feeder cable has the shortest segment where full power can be drawn. With same voltage but shorter cable, section 12 can provide full power for longer time. The most advantageous conditions has section 48 with the highest voltage and shortest feeder cable.

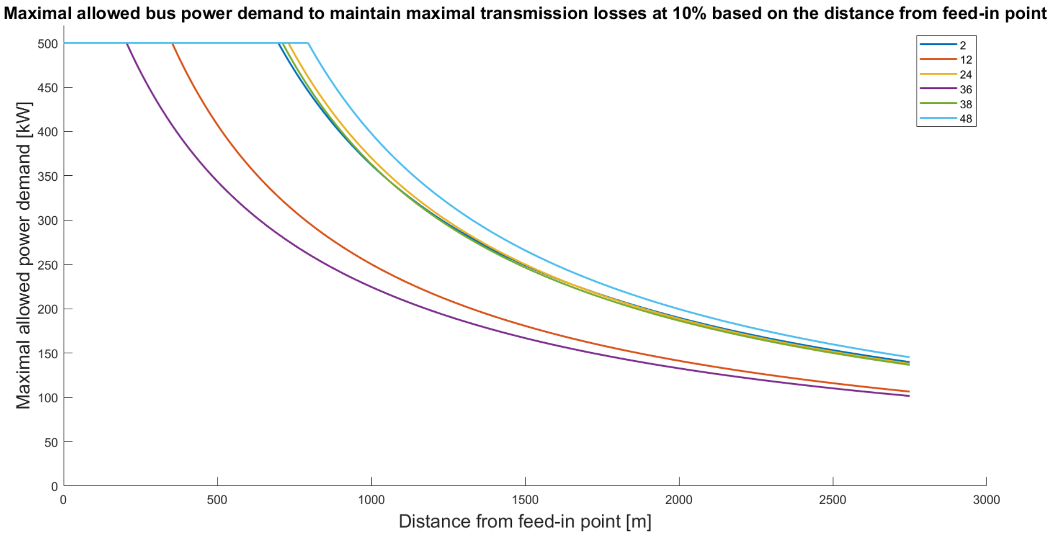


Figure 3.10: Maximal allowed bus power demand to maintain maximal transmission losses at 10% based on the distance from feed-in point

Table 3.4: Nominal voltage and feeder cable placement per section in Arnhem trolley-grid

Section	Substation Nominal Voltage [V]	Feeder cable length [m]
2	698	300
12	630	900
24	686	118
36	630	1350
38	685	170
48	700	20

In the figure 3.11, the effect of P_{cap} and curtailing the power drawn from the overhead lines is visible. Up until 730 [m] from the feed-in point, the curves are identical. This is exactly the distance, where the constant power demand of 500 [kW] would result in transmission losses over 10%. By limiting the bus power demand, both the voltage drop and the losses are mitigated.

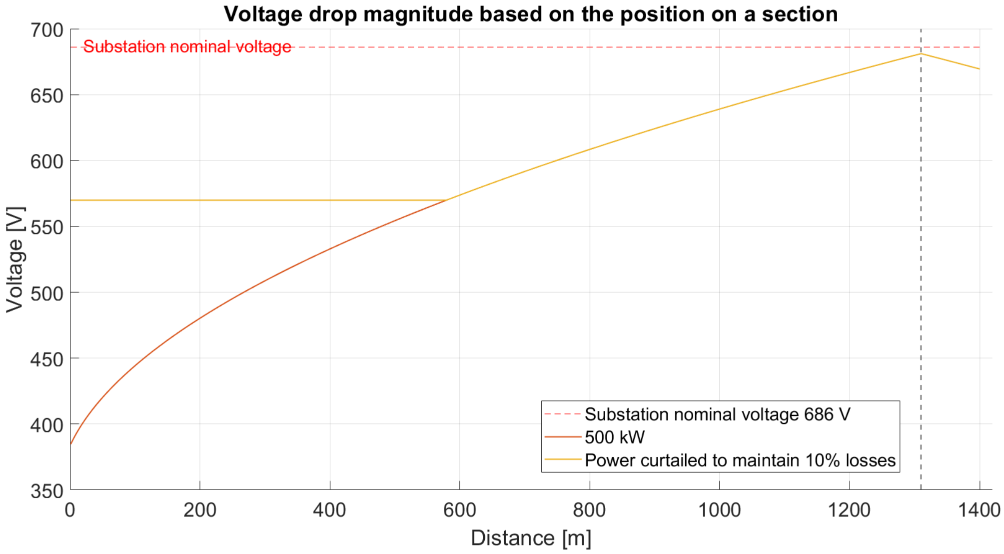


Figure 3.11: Voltage Drop magnitude based on the position on a section. Red line represents maximal constant power demand, yellow line represents the curtailed power demand to not go above 10% transmission losses. Nominal substation voltage 686 [V]. Vertical dashed line represents the feeder cable placement.

Voltage limit

The line voltage should never go below 490 [V] in order to secure safe and stable operation of the trolley-grid [4]. To determine the maximal power that complies with this limit, equation for bus power can be used:

$$P_b = V_b \cdot I_b \tag{3.15}$$

It is required to know what the bus power demand for the extreme case of voltage drop would be. The V_b can be substituted by $V_{min} = 490[V]$ which is the lower limit of bus voltage. To express also the current as a function of the V_{min}, simple voltage drop of the difference between the substation nominal voltage and the bus voltage which is now V_{min} and Ohm's law can be used to get:

$$P_b = \frac{V_{min} \cdot (V_s - V_{min})}{R} \tag{3.16}$$

The value of R stands for the total resistance of the electrical path of the current. In fact, it is the resistance that is dependant on the position of the vehicle on the section, or to be more specific, on its distance from the feed-in point. If the resistivity of overhead lines is ρ_o and the resistivity of feeder cable ρ_f in $[\Omega/m]$, the position of the bus X_b from the feed-in point and the length of feeder cable l_f are used:

$$P_{b,1} = \frac{V_{min} \cdot (V_s - V_{min})}{(\rho_o \cdot X_b) + (\rho_f \cdot l_f)} \tag{3.17}$$

The maximal allowed bus power demand to keep the bus voltage above 490 [V] is shown in the plot in 3.12. Even though the plot shows only 6 sections, the power cap had to be done for every single section separately because of the different parameters of each section.

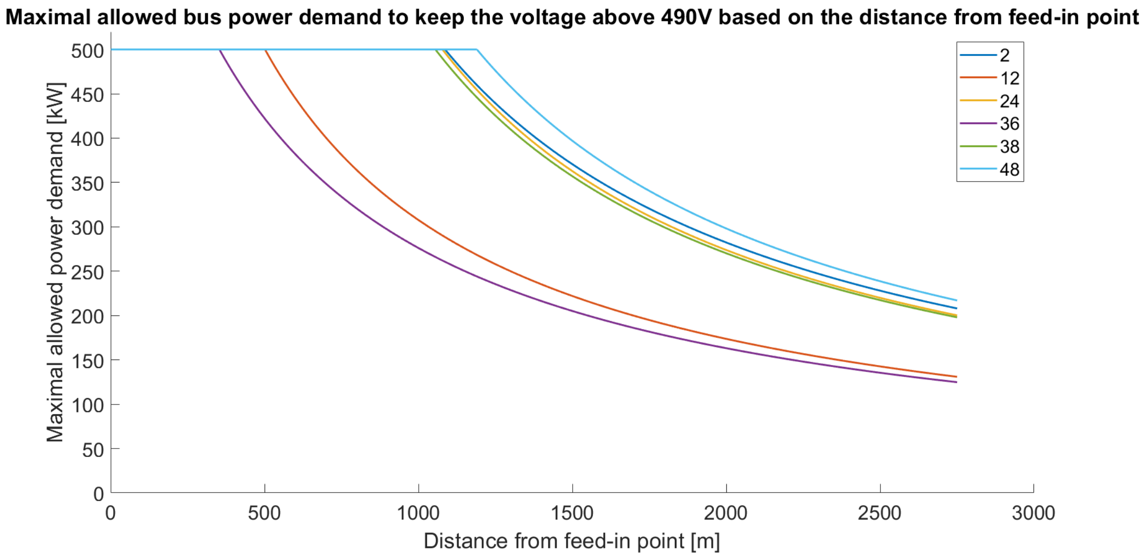


Figure 3.12: Maximal allowed bus power demand to keep the voltage above 490V based on the distance from feed-in point. Data for 6 section of Arnhem's trolley-grid

Current limit

The thermal limitation of overhead lines is described by current limit of $I_{\max} = 840[A]$. Similar process of determining the maximal allowed power as in the previous example will be used. Equation 3.15 still serve as the basis, just the current I_{b} is replaced by $I_{\max}$:

$$P_{\mathrm{b}} = V_{\mathrm{b}} \cdot I_{\max} \tag{3.18}$$

If the V_{b} is expressed as a function of $I_{\max}$ the same notation for R as in the case of voltage limitation is used, the power demand cap is:

$$P_{\mathrm{b},3} = (V_{\mathrm{s}} - (\rho_{\mathrm{o}} \cdot X_{\mathrm{b}} + \rho_{\mathrm{f}} \cdot l_{\mathrm{f}}) \cdot I_{\max}) \cdot I_{\max} \tag{3.19}$$

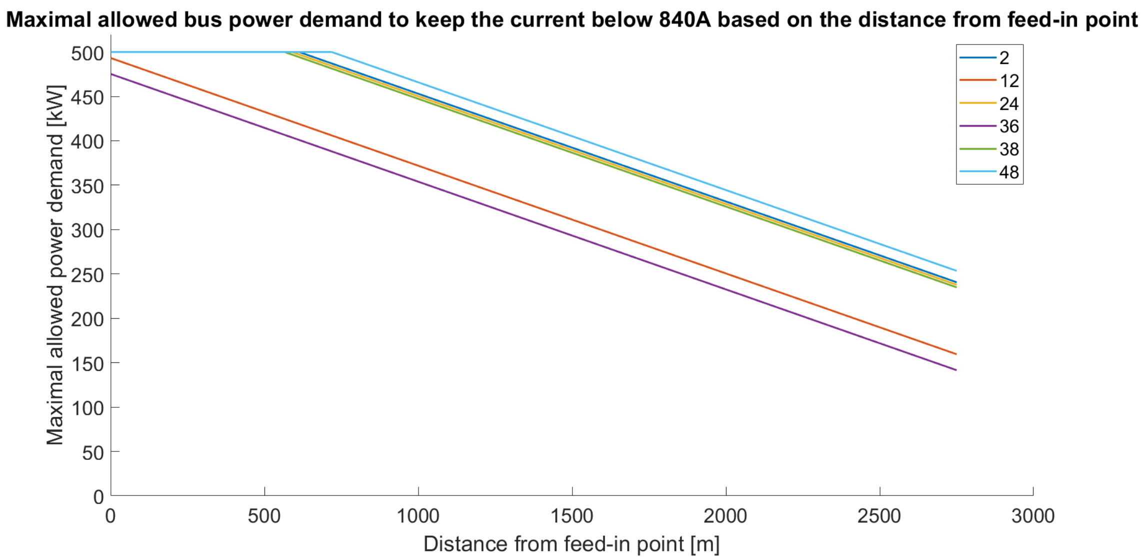
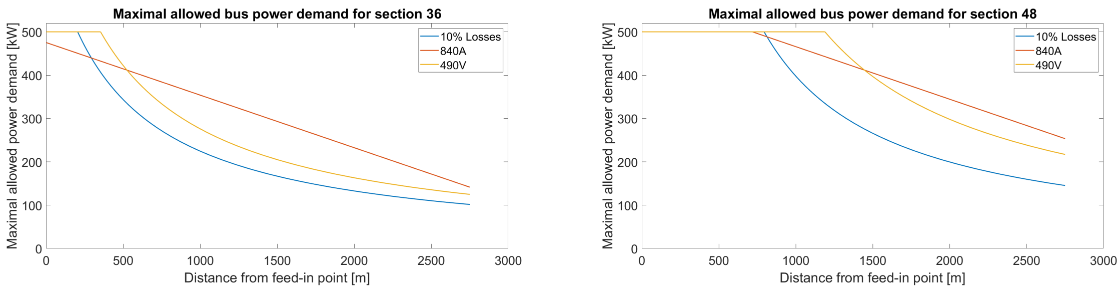


Figure 3.13: Maximal allowed bus power demand to keep the current below 840A based on the distance from feed-in point. Data for 6 section of Arnhem's trolley-grid

Summary
All the limitations listed and described above have determined the maximal allowed bus power demand to keep the voltage, current and transmission losses within safe values. For every [m] of distance from the feed-in point, power $P_{\mathrm{b},1}$, $P_{\mathrm{b},2}$ and $P_{\mathrm{b},3}$ apply. To get the final allowed power the minimal of the 3 limits has to be selected.

$$P_{\mathrm{cap,i}} = min(P_{\mathrm{b},1}, P_{\mathrm{b},2}, P_{\mathrm{b},3}) \qquad \forall i = 1 : 2750 \tag{3.20}$$

The value of i goes up to 2750 [m] as it is the maximal length of section. Out of these values, a look-up table has been made to select the maximal bus power demand based on the position of the bus from the feed-in point and the section the bus is connected to. As can be seen from 3.14, it is mostly the current and transmission losses factor that limit the power demand. For short distances from the feed-in point, it is the current limit, while with longer distances the effect of $P_{\mathrm{loss}} \sim I^2$ takes over and it is the transmission losses that have the minimal power based on equation 3.20.



(a) Section 36 (b) Section 48

Figure 3.14: Maximal allowed bus power demand for (a) section 36 and (b) section 48.

3.5.2. Multiple vehicles

For the purposes of calculation of the maximal power demand allowed when multiple trolleybuses are connected to the same section, a model situation will be used as in figure 3.15. The figure also shows all of the quantities that will be used for the calculation. As there is no possibility to tell the number of vehicles also connected and what their position on the section is, a static bus (EoL) will be placed at the end of each section. The trolleybus of our interest (1) will be moved on the section to capture this situation from every place on the section.

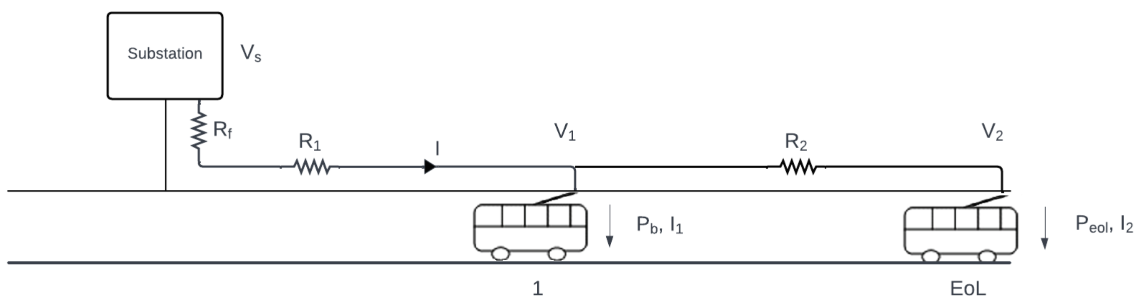


Figure 3.15: Illustration of model situation for determining the maximal bus power demand allowed when multiple buses are on the same section. Trolleybus 1 is the one of interest and it is moving on the section. Trolleybus EoL is standing still at the end of the section and drawing constant power

All of the values of maximal bus power demand calculated for one vehicle were based on the position from the feeder cable. The situation was exactly the same for both X [m] on the left from the feeder cable and X [m] on the right from the feeder cable. Now, when the EoL vehicle is placed at the end of the section, the fact that the distances on both sides from the feeder cable are not the same length has to be taken into account. Figure 3.16 explains the difference. Even though both buses labeled as 1 are at the same distance from the feeder cable, the buses labeled EoL standing at the end of the sections have different position relative to the feed-in point. They would also cause voltage drops of different magnitudes when drawing the same power.

The EoL trolleybus needs to demand certain amount of power. The trolley-grid can now include two types of trolleybuses, a regular trolleybus and IMC trolleybus. Both types should be reflected in the EoL's demand. On average, a trolleybus draws 70 [kW] for traction purposes and auxiliaries. To also include IMC, battery charging power will be included. As the trolleybus is standing at the end of the line, it would be forced to only take safe charging power, which is 50 [kW]. In total, the P_{eol} is:

$$P_{\mathrm{eol}} = 2P_{\mathrm{avg}} + P_{\mathrm{safe}} = 2 \cdot 70 + 50 = 190 \quad [kW]$$

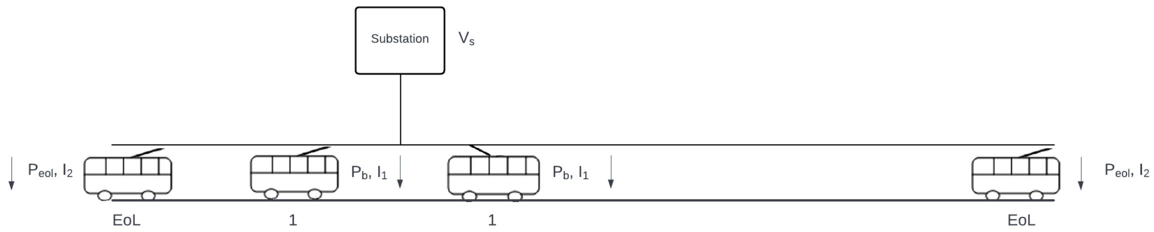


Figure 3.16: Illustration of right-hand and left-hand sides of the section from the substation being different in terms of having another vehicle drawing power at the end of the sections

Transmission losses limit
The target value of the maximal transmission losses remains the same as for the case of single vehicle, 10%. However, the equation used previously cannot be used as now also the other vehicle is affecting the total current in the overhead lines. Instead of determining the power cap analytically, an iterative approach was used. Unlike for the following ones where a mathematical expression could be easily derived, for knowing the transmission losses, trolley-grid simulations were performed.

The logic of the iterations is shown in figure 3.17. Based on which section was currently simulated, the data of feeder cable position S, total length of the section $x_{\max}$ or nominal substation voltage V_{s} were gathered. P_{eol} was kept constant, as already shown. The initial value of $P_{\mathrm{b},1}$ was set to be the maximal possible to start during the very first iteration, 500 [kW]. After the data initialization, the code is divided into two parts, one for each side of the section from the feeder cable. The FOR loops provide incremental position of trolleybus 1, either going from 1 to the feeder cable position or from feeder cable position till the end of the section. EoL trolleybus was placed at the corresponding end of the section. After that, the power flow simulation could be performed. According to the results, a fraction of transmission power losses of the total power demand of the two trolleybuses was calculated as:

$$\%_{\mathrm{loss}} = \frac{P_{\mathrm{loss}}}{P_{\mathrm{loss}} + P_{\mathrm{b},1} + P_{\mathrm{eol}}} \tag{3.21}$$

If the condition of the fraction being 10% of the total demand was not met, the WHILE loop returned the code at the beginning and decreased the $P_{b,1}$ value by 10 [kW]. This was repeated until suitable solution was found.

On both figures 3.18 and 3.19 the curtailment of trolleybus power demand can be seen. Obviously, in the areas around the feeder cable, which is marked as a vertical grey line in figure 3.19, the trolleybus is allowed to demand maximal power of 500 [kW]. The further the trolleybus is moved away from the feed-in point, the bigger the limitation is. Two cases worth noticing are sections 24 and 2. For section 24, there is more than a half of the section length where the trolleybus should not draw any power while there is another bus present to maintain the losses below 10%. For section 2, the curve goes gradually

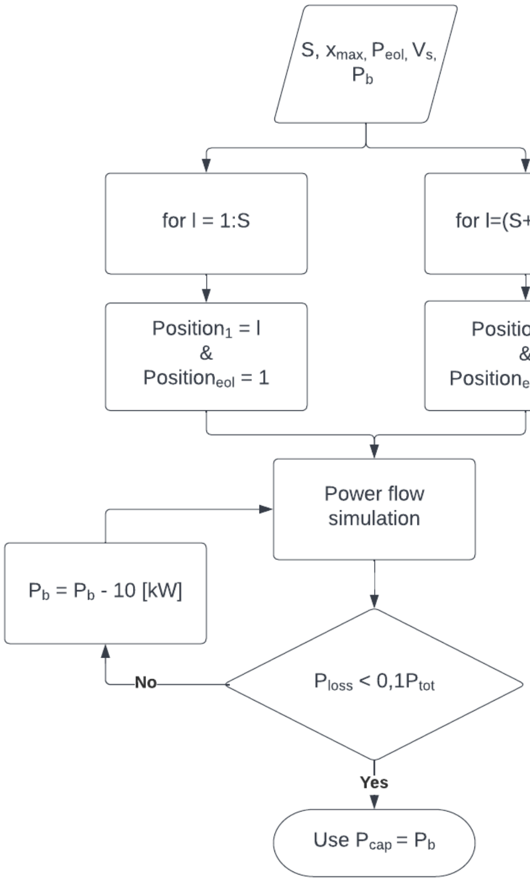


Figure 3.17: Flow diagram of iterative process for determining the maximal allowed power demand to keep 10% transmission losses in the case of multiple vehicles on one section

down until it reaches 10 [kW] at the end of the section. Even though these two sections are more or less of the same length and have almost the same placement of the feeder cable, the results are very dissimilar. The reason is in the nominal substation voltage which is higher for section 2. The higher the substation voltage, the lower the current in the overhead lines has to be to provide the power and thus the transmission losses are lower.

Table 3.5: Parameter comparison of sections 24 & 2 of the Arnhem trolley-grid

	Section 24	Section 2
Length [m]	1400	1300
Feeder cable [m]	1310	1210
Substation voltage [V]	686	698

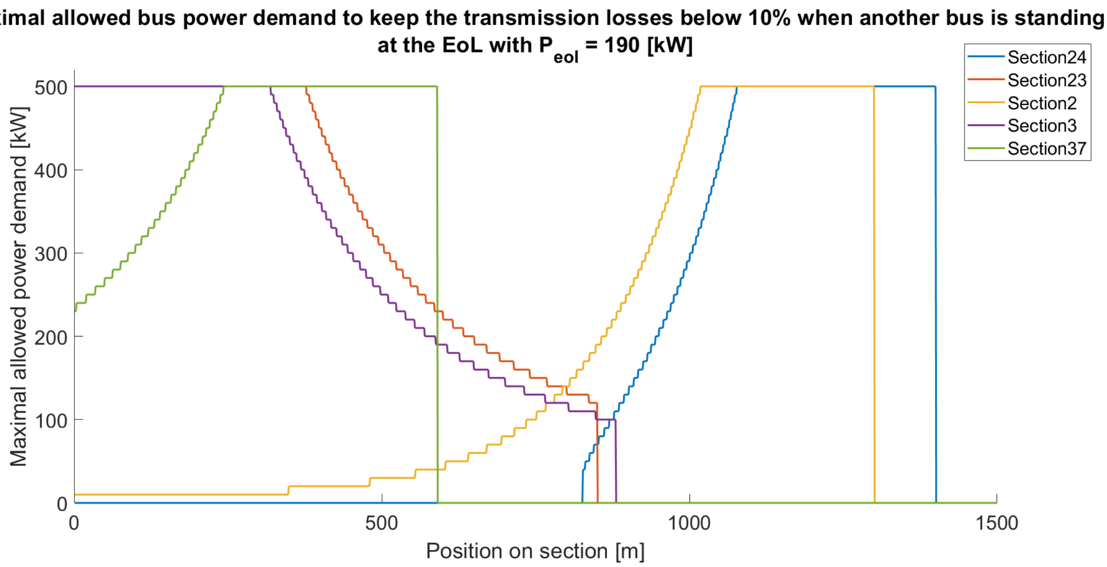


Figure 3.18: Maximal allowed bus power demand to keep the transmission power losses below 10% when there is another trolleybus standing at the end of the section and drawing $P_{\mathrm{eol}} = 190[kW]$. Results for section 24, 23, 2, 3 and 37 of the Arnhem trolley-grid

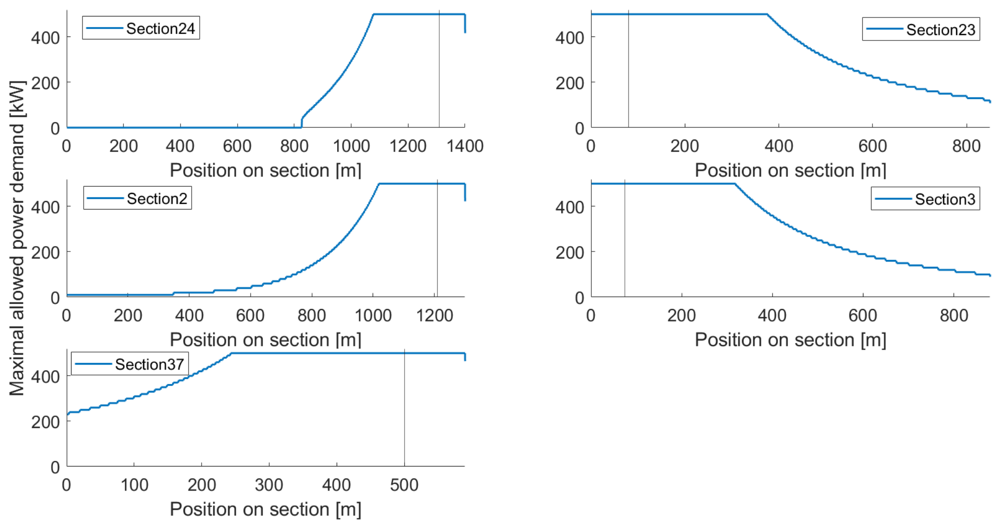


Figure 3.19: Maximal allowed bus power demand to keep the transmission power losses below 10% when there is another trolleybus standing at the end of the section and drawing $P_{\mathrm{eol}} = 190[kW]$. Plots separated for each section. Vertical lines sign the place of the feeder cable placement

Voltage limit

In order to come up with an expression to calculate the $P_b, 2$ based on the voltage limitation of 490 [V], figure 3.15 can be used to derive it. Similarly as in the previous calculation, the section had to be divided into two parts. Now it had to be done to figure out the right values of resistances R_1 and R_2. Both resistances are changing as trolleybus 1 is moved on the section.

for l = 1:S	for l = S:x_{max}
$R_1 = (S - l) \cdot r_{\mathrm{o}}$	$R1 = (l - S) \cdot r_{\mathrm{o}}$
$R_2 = (S \cdot r_{\mathrm{o}}) - R_1$	$R_2 = (x_{\mathrm{max}} \cdot r_{\mathrm{o}}) - R_1$

In the case of two trolleybuses on the same section drawing power from the overhead lines, the lowest voltage measured would be at the trolleybus further away from the feed-in point, which is the EoL trolleybus.

$$V_2 = 490[V]$$

The end of the section is also the point where the calculation has to start to get to the values of voltage and current of trolleybus 1. Now that the voltage and power of EoL are known, the current I_2 can be calculated as:

$$I_2 = \frac{P_{\text{eol}}}{V_2} \tag{3.22}$$

Knowing the current and the resistance between the two trolleybuses allow to get the voltage V_1:

$$V_1 = V_2 + R_2 I_2 = 490 + R_2 I_2 \tag{3.23}$$

Depending on what section the calculation is performed for, corresponding values of nominal substation voltage and feeder cable resistance R_{f} are used to determine the total amount of current that the substation has to supply based on the voltage drop between the substation and trolleybus 1:

$$I_{\text{total}} = \frac{V_{\text{s}} - V_1}{R_{\text{f}} + R_1} \tag{3.24}$$

As this is the sum of all currents, meaning I_1 and I_2, the current going into trolleybus 1 is:

$$I_1 = I_{\text{total}} - I_2 \tag{3.25}$$

The final value of $P_{\text{b},2}$ is a product of the trolleybus voltage and its current:

$$P_{\text{b},2} = V_1 I_1 \tag{3.26}$$

When the results from figures 3.20 and 3.21 are compared to the results of transmission losses limit, it can be seen that voltage does not pose that significant problem. Out of the 5 sections presented, only sections 24 and 2 have to use a power demand cap. It is once again caused by the length of the sections and therefore larger resistances resulting in larger voltage drops.

Current limit

When looking at the figure 3.15, the current limitation of 840 [A] now applies to the current going from the substation through feeder cable and R_1 to trolleybus 1 where it becomes I_1 and I_2. This time, the calculation starts at the substation side and continues further towards EoL. The way to come up with the resistances is the same as used previously. Firstly, the voltage of trolleybus 1 has to be calculated:

$$V_1 = V_{\text{s}} - (R_{\text{f}} + R_1)I_{\text{max}} = V_{\text{s}} - (R_{\text{f}} + R_1) \cdot 840 \tag{3.27}$$

Now that the voltage of trolleybus 1 is known, it is important to find out the current going to trolleybus EoL. From figure 3.15 it can be said that the current I_2 is provided exclusively by the node where trolleybus 1 is connected to the overhead lines. For the purpose of this calculation, this node can be claimed a virtual substation that feeds the branch going to trolleybus EoL which makes the computation easier. It allows to use an equation for voltage applicable to single bus on a section operation only which is:

$$V_{\text{b}} = \frac{V_{\text{s}} + \sqrt{V_{\text{s}}^2 - 4RP}}{2} \tag{3.28}$$

which in the notation of this case is:

$$V_2 = \frac{V_1 + \sqrt{V_1^2 - 4R_2 P_{\text{eol}}}}{2} \tag{3.29}$$

Now the current I_2 can be determined which together with the maximal current I_{max} gets I_1:

$$I_1 = I_{\text{max}} - I_2 = 840 - I_2 \tag{3.30}$$

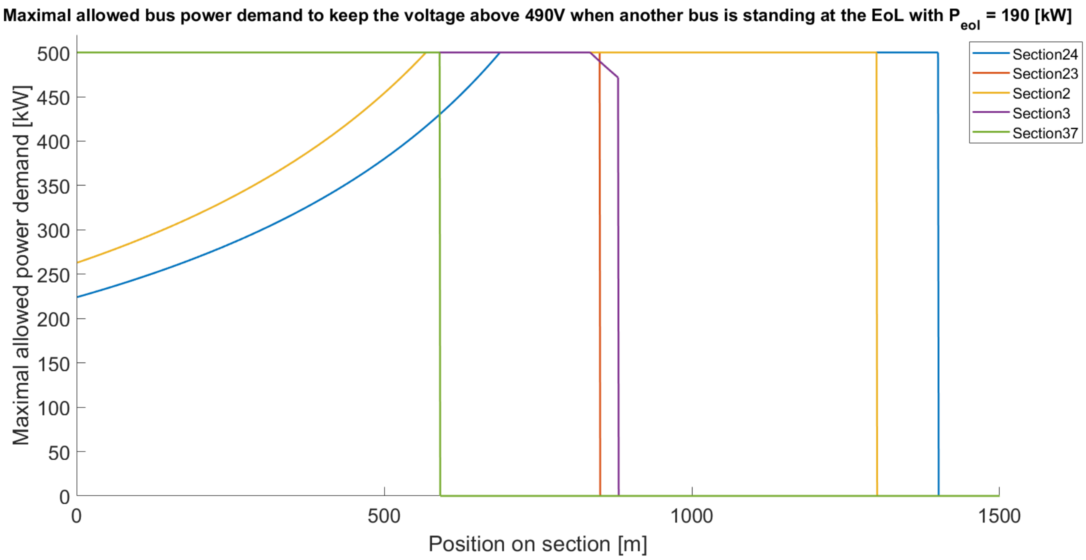


Figure 3.20: Maximal allowed bus power demand to keep the voltage above 490 [V] when there is another trolleybus standing at the end of the section and drawing $P_{eol} = 190[kW]$. Results for section 24, 23, 2, 3 and 37 of the Arnhem trolley-grid

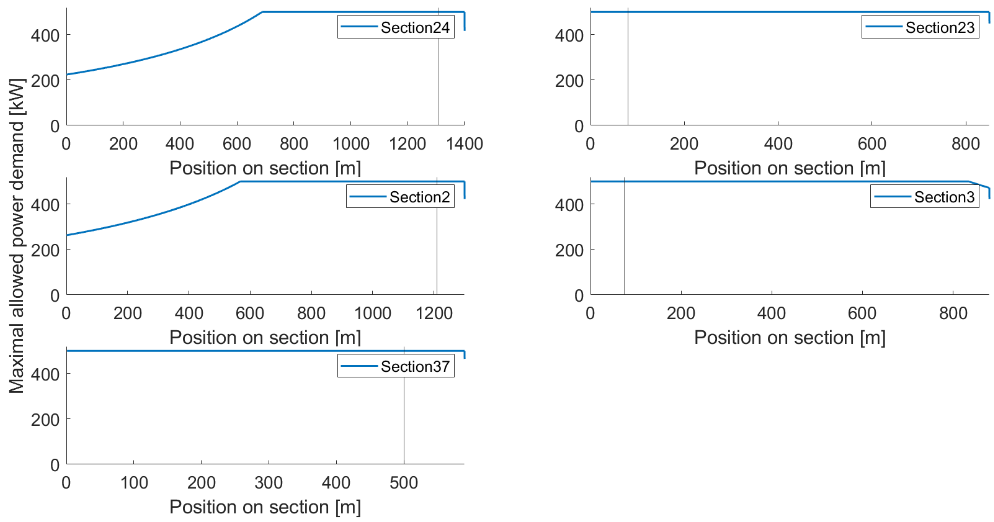


Figure 3.21: Maximal allowed bus power demand to keep the voltage above 490 [V] when there is another trolleybus standing at the end of the section and drawing $P_{eol} = 190[kW]$. Plots separated for each section. Vertical lines sign the place of the feeder cable placement

$P_{b,3}$ is then a product of voltage and current:

$$P_{b,3} = V_1 I_1 \tag{3.31}$$

Apart from transmission losses and voltage limitations, current limitations caps the maximal power demand allowed already at the feeder cable so there are no regions where 500 [kW] could be drawn from the overhead lines in case of multiple vehicles on one section. On the other hand, when compared to the previous plots which have more of a hyperbolic shape and thus rather faster decrease, the current cap is more steady and on no occasion prevents the trolleybus from drawing no power at all.

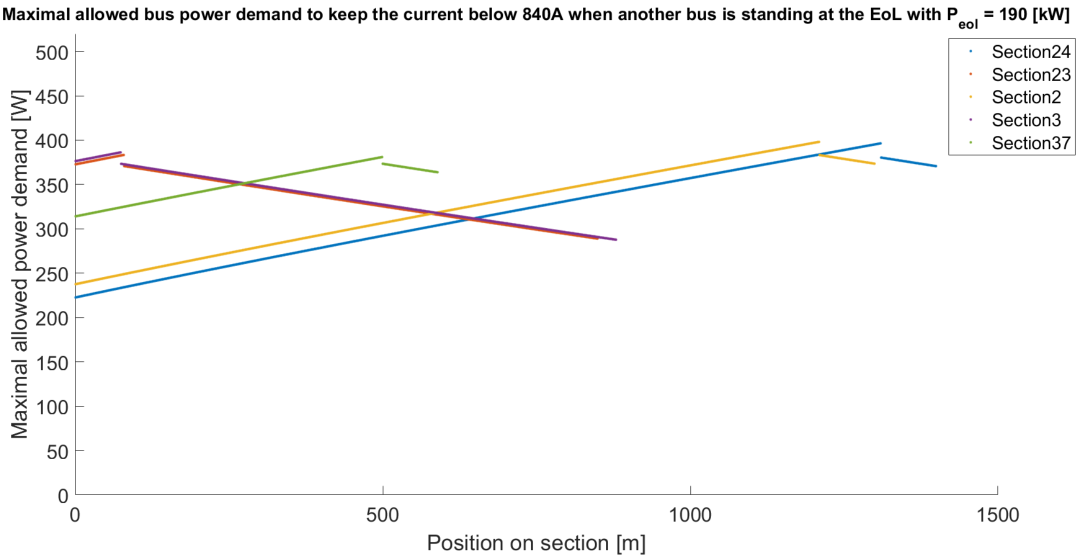


Figure 3.22: Maximal allowed bus power demand to keep the current below 840 [A] when there is another trolleybus standing at the end of the section and drawing $P_{\text{eol}} = 190[kW]$. The difference at the peaks of the lines is caused by the distinct positions (distance from feeder cable) of the EoL vehicle. Results for section 24, 23, 2, 3 and 37 of the Arnhem trolley-grid

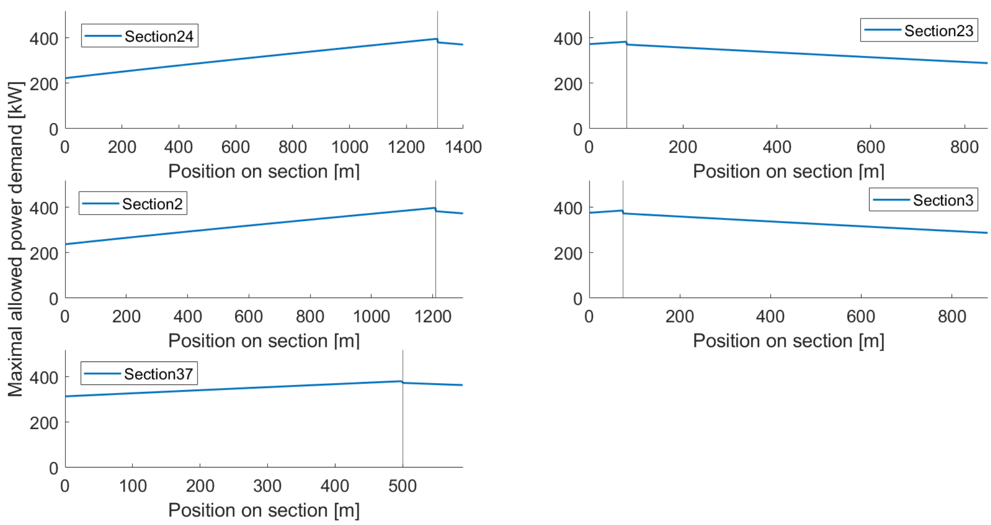


Figure 3.23: Maximal allowed bus power demand to keep the current below 840 [A] when there is another trolleybus standing at the end of the section and drawing $P_{\text{eol}} = 190[kW]$. Plots separated for each section. Vertical lines sign the place of the feeder cable placement

Summary
Same as for the case of single vehicle, a look-up table of minimal values of power based on voltage, current and transmission loss limitation has been made for every section of Arnhem trolley-grid according to equation 3.20. Figure 3.24 shows a combination of the three limitation curves for section 3 in Arnhem. It is visible that the current limitation affects the maximal power near the feeder cable while voltage and transmission losses would allow for maximal power. The further away the trolleybus gets, the more start the transmission losses to take over.

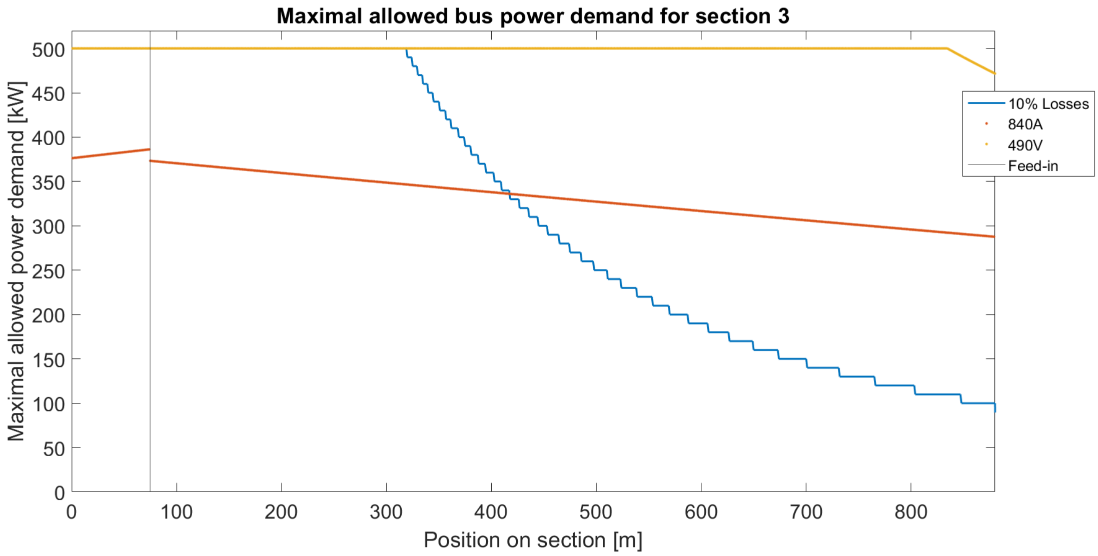


Figure 3.24: Maximal allowed bus power demand on section 3 when there is another trolleybus standing at the end of the section and drawing $P_{\text{eol}} = 190[kW]$

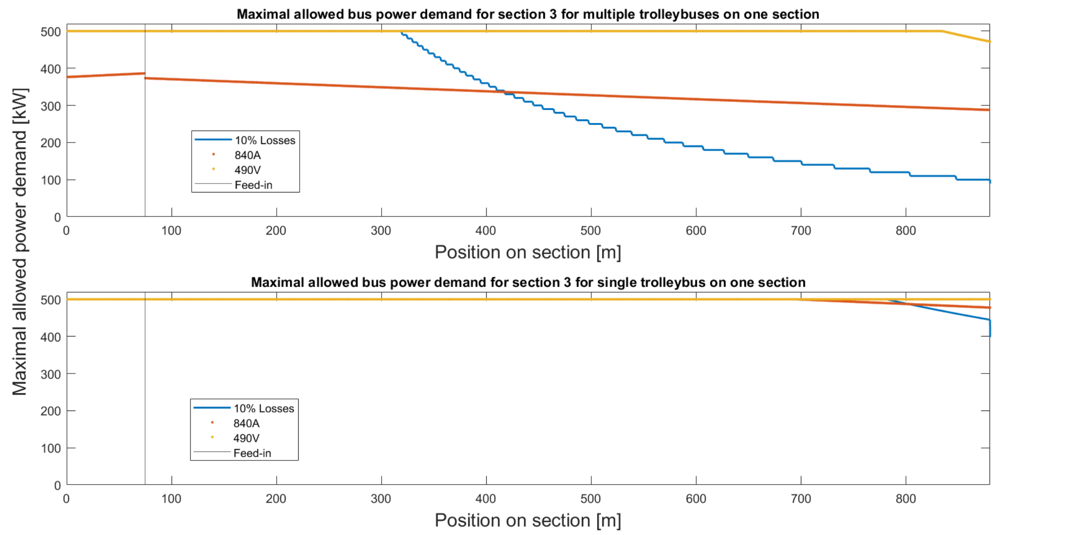


Figure 3.25: Comparison of power demand cap for single vehicle on a section and multiple vehicles on a section. Data for section 3 of Arnhem trolley-grid

Now that the power cap has been made for case of one and multiple vehicles connected to one section, these findings can be compared in figure 3.25. The effect another vehicle placed at the end of the section has on the demand is significant, especially in terms of the transmission losses. Single vehicle on section 3 could demand almost 450 [kW] while when two vehicles are there (and one of them draws

190 [kW]) the power can only be 100 [kW]. This proves the significance of transmission losses mainly on long sections. An interesting fact is that the limitation of voltage has not been affected that much by a presence of a second trolleybus.

3.6. Feeder Cable Placement

To understand how the measured values of bus voltage and bus current are affected by a presence of another vehicle, it is necessary to look at their mutual position to the substation feed-in point. For the purposes of trolley-grid estimator it is of great importance to be able to detect the effect of other vehicles' interaction with the trolley-grid. The effect of the feeder cable placement will be shown on two possible examples: feeder cable at the end of a section and feeder cable in the middle of a section. Two vehicles will be connected on the same section.

3.6.1. Feeder cable at the end of a section

Initial case with only one vehicle on a section is shown in figure 3.26. The substation now only has to feed one vehicle. This results in a voltage drop at the connection point of the current collector and the overhead line caused only by the current drawn by vehicle 1. The measurement device of the vehicle would sense these values of voltage and current:

$$V_{\mathrm{b},1} = 690,56[V] \mid I_{\mathrm{b},1} = -144,81[A]$$

Figure 3.26: One trolleybus connected to a section fed at the end. Vehicle is drawing power of 100 [kW] at a distance of 200 [m] from the substation. Substation nominal voltage 698 [V].

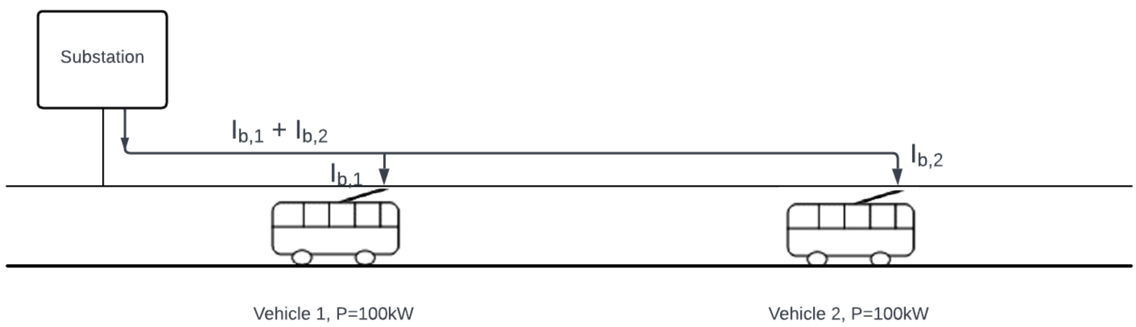


Figure 3.27: Two trolleybuses connected to a section fed at the end. Vehicle 1 is drawing power of 100 [kW] at a distance of 200 [m] from the substation. Vehicle 2 is drawing power of 100 [kW] at a distance of 500 [m] from the substation. Substation nominal voltage 698 [V].

If another vehicle is added further from the substation than vehicle 1 is, the situation will look like in figure 3.27. The total substation current now comprises of the current for traction of vehicle 1 $I_{\mathrm{b},1}$ and the current for traction of vehicle 2 $I_{\mathrm{b},2}$. Even though the traction power is the same as in the previous example, vehicle 1 will see much larger voltage drop caused by the sum of these two currents. Vehicle 2 will see a voltage of vehicle 1 decreased by a voltage drop caused by $I_{\mathrm{b},2}$.

$$V_{\mathrm{b},1} = 675,22[V] \mid I_{\mathrm{b},1} = -148,1[A]$$

The same results would be obtained when vehicle 1 is further from the substation than vehicle 2 (vehicles switch positions). The voltage drop for vehicle 1 would be larger due to the increased distance from the substation.

3.6.2. Feeder cable in the middle of a section

When the feeder cable is placed in the middle of the section as shown in figure 3.29, there is a possibility of two vehicles being connected to the same section but on opposite sides from the feeder cable. If in the case of single vehicle on a section the distance from feeder cable and traction power are kept at 200 [m] and 100 [kW], respectively, the same results as for the case from 3.26 will be obtained. Simulation of two buses as shown in figure 3.28 reveal that the effect of the vehicle to each other's voltage and current is only minimal. The voltage changes by almost 2,5 [V] and the current by almost 1 [A]. As the vehicles does not share the same electrical path for their currents, only the feeder cable resistance voltage drop is affected by the sum of the currents. For this simulation, feeder cable length was assumed to be 300 [m], which would already cause a drop of 5 [V]. It means the shorter the feeder cable is, the lower the deviation of voltage and current in such case is. Considering certain measurement error, such little deviations should not serve as a decision makers for the trolley-grid estimator. The estimator needs to seize the measurements and decide whether more vehicles are affecting them and the feeder cable in the middle prevents to do so on many occasions when the vehicles are on opposite sides.

$$V_{\mathrm{b},1} = 688,07[V] \mid I_{\mathrm{b},1} = -145,33[A]$$

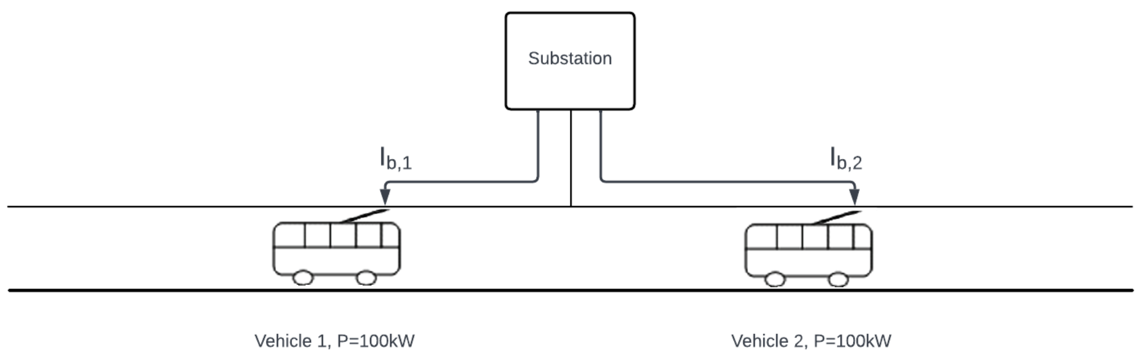


Figure 3.28: Two trolleybuses connected to a section fed in the middle. Both vehicles are drawing power of 100 [kW] at a distance of 200 [m] from the substation on the opposite sides. Substation nominal voltage 698 [V].

As a result, the sections with feeder cable placed at the end are considered suitable for the purposes of the trolley-grid estimator as the changes in voltage and current are measurable. Considering the case study of Arnhem trolley-grid, figure 3.30 shows the relative position of the feeder cable on a section. Values close either to 1 or 0 show placement at the beginning/end of the section. As can be seen, the vast majority of sections is built in the desired fashion. Due to the uncertainty linked to the vehicle "blinding" on sections with a feeder cable in the middle presented above, an assumption is made that the IMC vehicles will only charge P_{safe} to prevent the grid from failure.

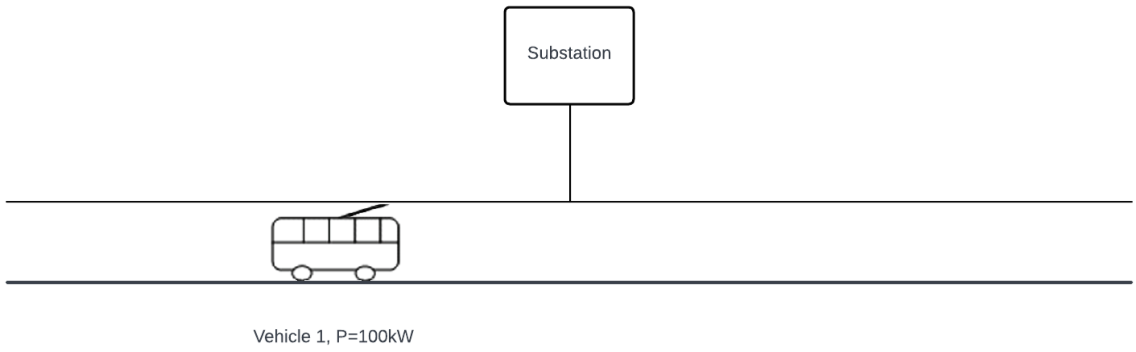


Figure 3.29: One trolleybus connected to a section fed in the middle. Vehicle is drawing power of 100 [kW] at a distance of 200 [m] from the substation. Substation nominal voltage 698 [V].

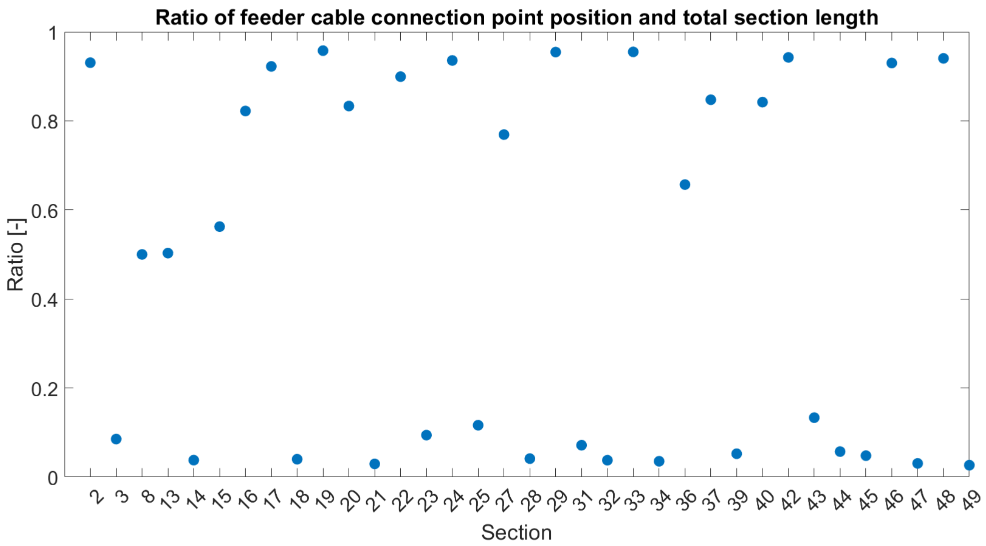


Figure 3.30: Ratio of feeder placement and section length. Section length goes from 0 to total section length $x_{\max}$. Feeder cable connection point is the distance from the beginning of the section. In Arnhem, most feeder cables are either connected at the beginning or at the end as the ratio is either close to 0 or to 1, respectively. If the ratio is around 0.5, the estimator might malfunction and the IMC trolleybus should charge safe charging value P_{safe}

3.7. Section switching

Special attention has to be brought to the moment when the trolleybus is leaving one trolley-grid section and is about to enter the following one. Two trolley-grid sections are physically separated by a place where there is no overhead line. This allows the two sections to have different technical parameters, most importantly a different substation nominal voltage. When the two neighbouring sections do not have the same feeding substation, their nominal voltages differ which could cause inadequate voltage drops when crossing the sections. The same power demand would cause much larger voltage drop when the nominal substation voltage is lower in the next substation. Also, as shown in sections 3.5 and 3.6, the position of the trolleybus according to the feeder cable of the substation matters.

3.8. Concept of initial current and initial voltage

The power flow calculations performed by the MATLAB mathematical model of trolley-grid may take a lot of iterations, especially in case of multiple vehicles connected to the same section. For one vehicle only, the calculation of bus line voltage and bus current can be done by simple analytic equations describing the electrical circuit. The results are either the same or very close to the values determined by the mathematical model. These equations are only valid for the case of one vehicle on a section as the calculations for multiple vehicles are more complex. For the purposes of this thesis, the results of these equations are called V_σ for bus line voltage and I_σ for bus current.

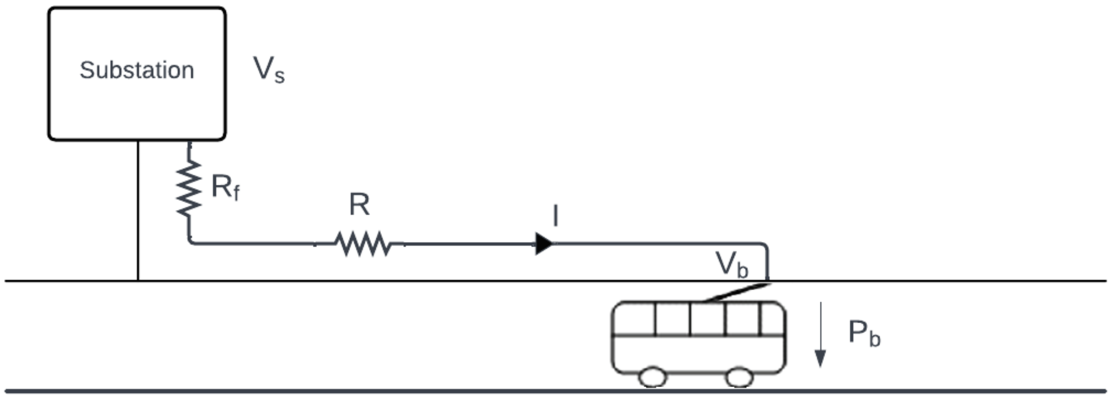


Figure 3.31: Illustration of electrical path from substation to vehicle. One vehicle on section. S - Substation, V_s - Substation nominal voltage, R_f - Feeder cable resistance, I - Current, R - overhead line resistance, P - Bus Power

Figure 3.31 depicts a situation when only one trolleybus is connected to a section fed by a single substation. This trolleybus is currently drawing power P from the overhead lines for traction purposes. There is an illustration of the electrical path for the current going from the substation to the vehicle. It consists of the resistance of the feeder cable R_f and of the resistance of overhead lines R. The origin of the power supply is at the substation with nominal voltage V_s. The total power P_s that the substation has to provide consists of two parts:

$$P_\mathrm{s} = P_\mathrm{b} + P_\mathrm{loss} \tag{3.32}$$

where P_b is the bus power demand and P_loss is the transmission losses in the form of heat in the feeder cable and the overhead lines. If the equation 3.32 is reformulated so as P_b is now the desired quantity, following equation is obtained which is just a different notation of a quadratic equation 3.34:

$$P_\mathrm{b} = V_\mathrm{s}I - R * I^2 - R_\mathrm{f} * I^2 \tag{3.33}$$

$$0 = (-R - R_\mathrm{f})I^2 + V_\mathrm{s}I - P_\mathrm{b} \tag{3.34}$$

with roots of:

$$I_{1,2} = \frac{-V_\mathrm{s} \pm \sqrt{V_\mathrm{s}^2 - 4(-R - R_\mathrm{f})(-P_\mathrm{b})}}{2(-R - R_\mathrm{f})} \tag{3.35}$$

The meaning of the two roots can be understood the best from Vieta's formulas which give relations between the coefficients of the quadratic equation and its roots. According to them, the roots p and q should be given as:

$$-\frac{b}{a} = \frac{Vs}{R + R_\mathrm{f}} = p + q \tag{3.36}$$

$$\frac{c}{a} = \frac{P_\mathrm{b}}{R + R_\mathrm{f}} = pq \tag{3.37}$$

As it is know that one of the roots is the bus current I_b, it is simple to derive what the root q represents. The fraction from equation 3.36 is equal to the total current that the substation has to supply. When the root p is deducted to get the root q, it leaves the equation with following form which determines the sum of currents from other branches except from the current meant for the concerned bus:

$$q = \frac{Vs}{R+R_\mathrm{f}} - p = \frac{Vs}{R+R_\mathrm{f}} - I_\mathrm{b} = I_\mathrm{tot} - I_\mathrm{b} \tag{3.38}$$

The same computational logic can be applied to the calculation of bus voltage V_b. The quadratic equation with roots is:

$$V^2 - V_\mathrm{s}V + RP = 0 \tag{3.39}$$

$$V_{1,2} = \frac{V_\mathrm{s} \pm \sqrt{V_\mathrm{s}^2 - 4(R+R_\mathrm{f})P_\mathrm{b}}}{2} \tag{3.40}$$

If $p = V_\mathrm{b}$, then the other root of q equals to:

$$q = V_\mathrm{s} - V_\mathrm{b} \tag{3.41}$$

This formula is valuable because it gives us an information of what the voltage drop with the certain P_b on certain position reflected in $(R+R_\mathrm{f})$ would be when the vehicle is alone on section. Both the second roots of quadratic equations for current and voltage can give another insight into the behavior on the section. If we get back to the initial point of the calculations, I_b and V_b, they can be referred to as:

$$I_\mathrm{b} = I_\sigma \tag{3.42}$$

$$V_\mathrm{b} = V_\sigma \tag{3.43}$$

Knowledge of I_σ and V_σ provides very first understanding of what is happening on the section. As they have the meaning of bus voltage and bus current when the vehicle is the only one connected to the section, one can tell whether some aspect of the operation is different. More vehicles connected to the section or total excess of energy when other vehicles are braking could be mentioned as examples.

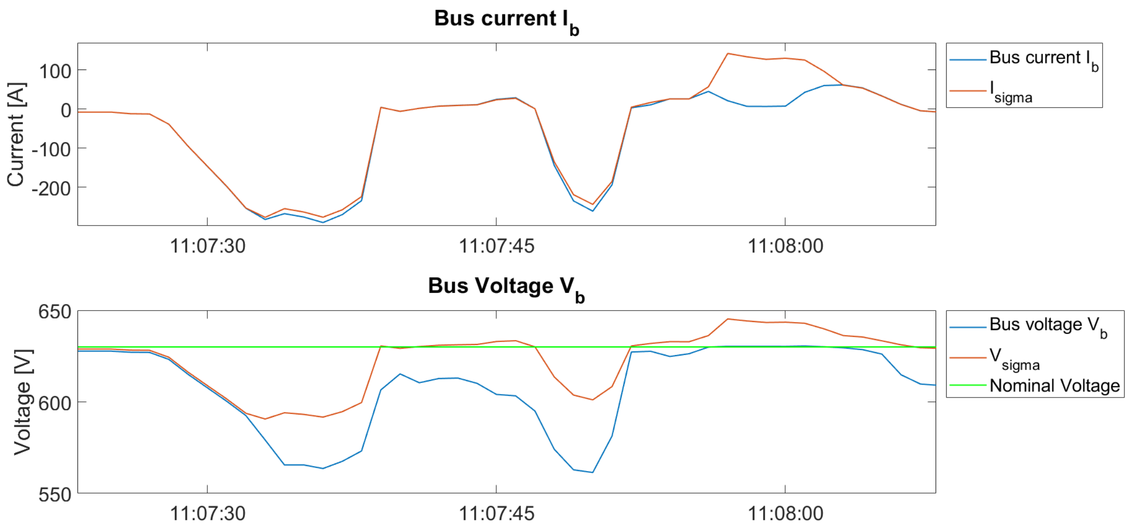


Figure 3.32: Example of I_σ and V_σ not being equal to I_bus and V_bus, respectively

Figure 3.32 depicts an example of a trolleybus operation case when the comparison of I_σ and V_σ clearly shows that the trolleybus is not alone on the section. The difference in voltage seems more obvious than in current, but it is just a matter of scale. The I_σ value can be 20 [A] higher than I_bus. There is also a moment when the current goes into positive values, meaning braking of the trolleybus. As the actual bus current is also positive, it can be deducted that there is another trolleybus drawing power from the grid and is accepting some of the braking energy. In case of actual bus current of 0 [A], the other trolleybus would also be braking.

Even though equations 3.42 and 3.43 show that I_b and I_σ should be equal in case of alone operation on the section, the calculated value I_σ slightly differs, mostly in 10^{-2} [A]. For this reason, a tolerance had to be established which would tell if the two values are similar or not. The trolley-grid model also works with a resolution of 0,2 [A]. It performs iterations of power flow calculations to reach certain level of convergence and if two consecutive current values do not differ by more than 0,2 [A], the iterative loop is quit and the simulation moves on. The tolerance needs to make sure that the difference between these two values is not caused by a resolution error of the trolley-grid model and also has to provide some margin. An approach of using a value at least two times higher than the resolution (the largest mistake of the model) is suggested here.

$$tolerance_{\mathrm{I}\sigma} >= 2 \cdot tolerance_{\mathrm{model}} \tag{3.44}$$

Having stated that, a tolerance for comparing I_b and I_σ of 0,5 [A] has been used.

An analysis of initial bus power has also been carried out. This value of initial power tells what the power demand of the vehicle must have been in order to cause such voltage drop the vehicle can measure. A way to estimate the maximal current in the overhead lines with the help of this value was investigated. The methodology and the findings are presented in the appendix E.

4
Early Valley-Charging Estimator Versions

This chapter describes the development process of the estimator and validation of the available power capacity estimation methods. When the estimation methods fails, the case is thoroughly studied. Section 4.1 introduces the reader the simulation background such as the new IMC line. Section 4.2 starts with providing results of initial state of the Arnhem trolley-grid for reference to the further results of this thesis. The simulation results of a scenario where the perfect communication between all vehicles on the grid are in section 4.3. Section 4.4 follows with simulation results with previous versions of the estimator.

4.1. Simulation Setup

Simulations of public transport should usually cover one whole year of operation. Mainly to capture any daily-basis delays, changes of routes, etc. The MATLAB simulations used for this thesis use timetable data sets where just a little uncertainty has been added to account for the delays. That means that especially same types of days would have very similar results throughout the whole year. For this reason, 6 representative days summarized in table 4.1 will be simulated. They all stand for different types of days with different traffic situation and most importantly capturing the seasonal change reflected in the consumption of HVAC. It is worth mentioning that the numbers of the days specified in the table are applicable to the year 2020. This approach has also been selected to work with the result data in more detailed fashion and to be able to focus on special circumstances that occur during the simulations. It can also allow to use this feedback of how favorable the results are into developing more sophisticated versions of the estimator.

Table 4.1: Overview of the days of the year 2020 to be simulated as the representative days capturing variation in traffic and seasonal changes

Day Schedule	Date	Category	Traffic	Auxiliaries (HVAC)
1	1.1.2020	School holiday week	High	High (winter)
117	26.4.2020	Sunday & special holiday	Low	Low (spring)
197	15.7.2020	Summer weekday	Low	Medium (summer)
200	18.7.2020	Summer Saturday	Low	Medium (summer)
268	24.9.2020	Regular weekday	High	High (winter)
305	31.10.2020	Regular Saturday	Low	High (winter)

To address RQ2 stated at the beginning of section 3, a diesel bus line of Arnhem public transport system has been turned into a more sustainable and environmentally friendlier electrified IMC trolleybus line. This does not only mean new load for the substations of Arnhem trolley-grid caused by the battery charging but also an extra load needed just for traction purposes of newly added vehicles. For the purposes of this thesis, a line number 352 going from Arnhem Centraal (A) to Wageningen (W) has been chosen. It consists of 9 vehicles in total which in this thesis were given numbers of:

Line 352 IMC trolleybus numbers	[40 41 42 43 44 45 46 47 48]

Figure 4.1 depicts the route line 352 has to take. When the vehicles sets off from A, it starts its operation as an IMC trolleybus connected to the overhead lines of Arnhem trolley-grid. The last bus stop after which the vehicle exits the trolley-grid and has to turn into autonomous mode and use battery for traction is Oosterbeek, Gemeentehuis and is marked in the figure.

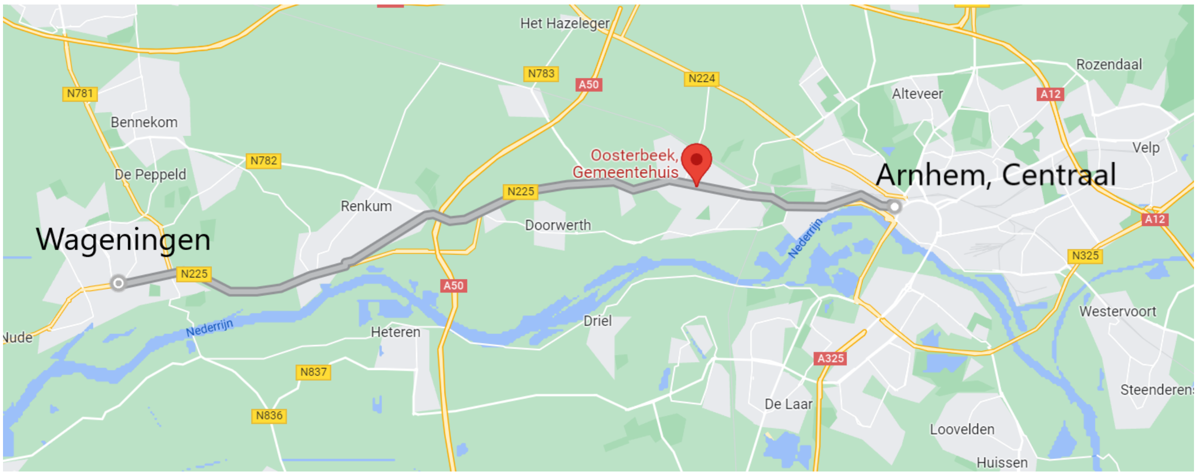


Figure 4.1: Line 352 route going from Arnhem Centraal to Wageningen. Bus stop of Oosterbeek, Gemeentehuis is the last bus stop within the Arnhem trolley-grid

Table 4.2: Distance between Arnhem Centraal and both Oosterbeek, Gemeentehuis and Wageningen

Trip	Distance [km]
Arnhem Centraal to Oosterbeek, Gemeentehuis	4,4
Arnhem Centraal to Wageningen	17,3

The part of the route covered with overhead lines where the IMC vehicle can charge its battery is 4,4 [km] long. It is approximately 25% of the total trip from A to W. The IMC line 352 has been designed as a range extension line, meaning the IMC vehicle which is being charged within the trolley-grid leaves it to operate in autonomous mode. It also needs to get back the same way still being dependent on its on-board battery. When looking at the route from this perspective, the IMC vehicle has to be able to cover a trip of around 26 [km] in one go before it enters the Arnhem trolley-grid again.

Table 4.3: Parameters of trolley-grid sections of line 352 route

Section	Length [m]	Feed-in point [m]	Substation nominal voltage [V]
24	1400	1310	686
23	850	80	686
2	1300	1210	698
3	880	75	698
37	590	500	685
38	-	-	685

Within the Arnhem trolley-grid, the IMC vehicles travel through 6 trolley-grid sections. They are captured in figure 4.2 and their parameters can be inspected in table 4.3. Special attention should be paid to section 38. It only consists of the Arnhem Centraal Station so the parameters of length and placement of the feed-in point are not relevant. In figure 4.2, the place where the feed-in point is can be

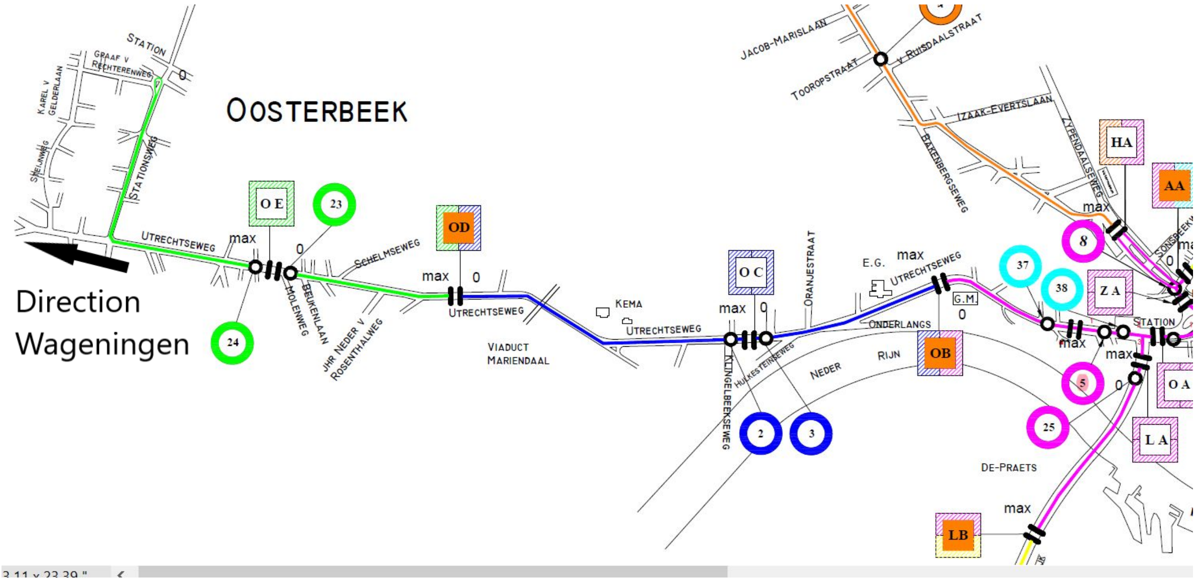


Figure 4.2: Line 352 route in the Arnhem trolley-grid. Map of sections

Table 4.4: Substations feeding trolley-grid sections of line 352 route

Substation	Sections fed	Substation nominal voltage [V]	Power demand limit [kW]
1	[2 3 4]	698	800
12	[23 24]	686	800
21	[37 38]	685	2600*

recognized as the place from which the circle with the number of section is connected to. In total, there are 3 substations providing power to the aforementioned sections, their overview is in table 4.4. For substation 21 feeding section 37 and section 38 (AC), the power demand limit is significantly higher than for the other substations. This total limit shelters more sections at a time, namely [37 38 5 6 8 25]. During the simulations and for the sake of the results, this fact has been accounted for.

4.2. Trolleybus Operation Only

The trolley-grid sections included in the route of line 352 presented in table 4.3 are shared with other lines of Arnhem public transport system. They are exclusively regular trolleybus without any on-board storage. Except for section 38, which is the A station and every single trolleybus from all the lines in Arnhem pass through, the remaining sections are only used by line 1 going from Oosterbeek to Velp. This line is comprised of 6 trolleybuses. The possibility of meeting other vehicles on the same section increases the risk of violating the technical limits of either substation or the overhead lines. These results only deal with the regular trolleybuses that are already in operation in Arnhem nowadays and show how the trolley-grid operation looks initially. No IMC trolleybuses are considered here.

Day 1 & 268
As line 1 with the 6 vehicles has already been in operation in Arnhem, even the simulation results are almost problem-free. The substation power demand limit of 800 [kW] is not broken even during the busiest or most energy demanding days of the whole year, day 1 and day 268 respectively (figures 4.3 and 4.4). Most of the time, total demand does not achieve half of the limits as only on few occasions the demand is as high as 630 [kW] for substation 12. Even though substation 21 experiences higher power demands, it has to be mentioned that its capacity is significantly increased compared to other substations due to the high traffic at the A station.

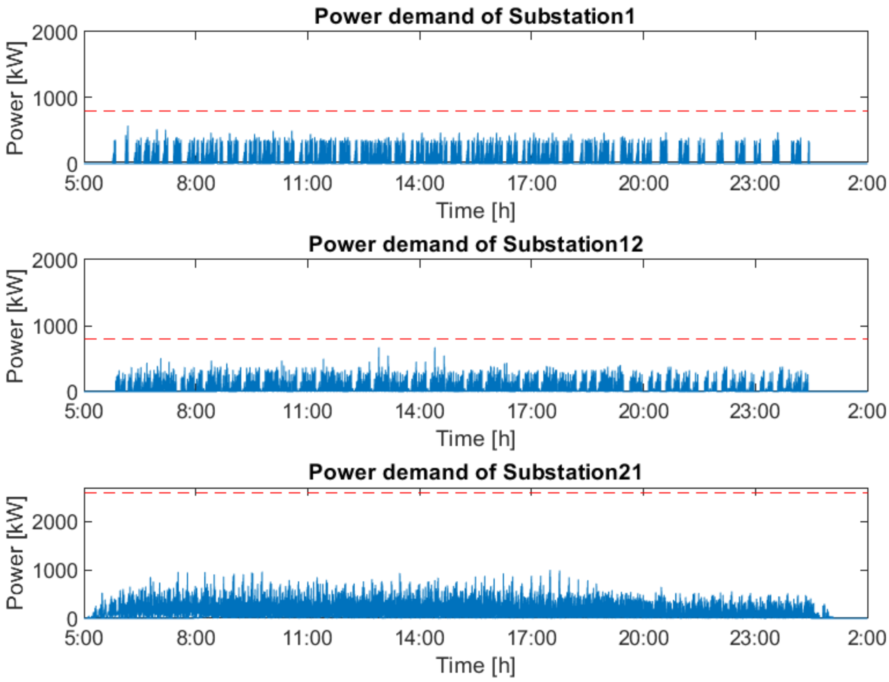


Figure 4.3: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Initial trolleybus only scenario.

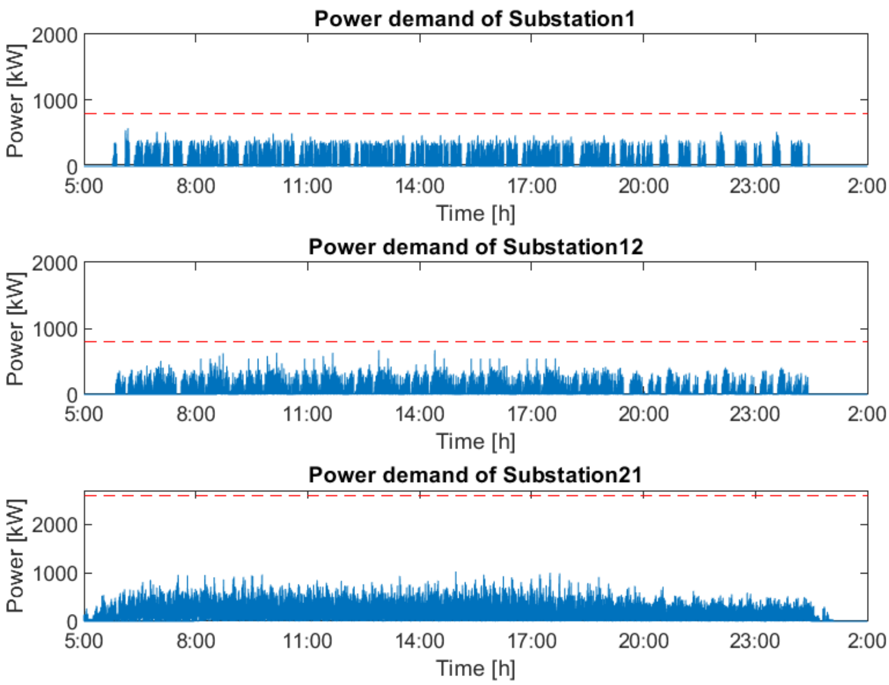


Figure 4.4: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Initial trolleybus only scenario.

The minimal voltage on each section for these two days presented is also very much within the acceptable range, not putting the feeding substation into jeopardy of voltage imbalance. There is one voltage drop standing out from the rest in figure 4.6. It belongs to the same time step as the highest power demand on substation 12 in figure 4.4 is. Not so favourable results for this trolleybus-only scenario can be seen in figures 4.7 and 4.8 with regards to the current limitation of 840 [A] on each section. During day 1 (figure 4.7), there are only short-lasting violations on section 38 caused by high traffic. Same as the one violation on section 38 during day 268, the traffic was at least of 5 vehicles, where some of them required just 5 [kW] for auxiliaries while taking a break but other trolleybuses already set off for another trip and accelerated resulting in very high power demand. Day 268 (figure 4.8) experienced problems also on other sections, namely 23 and 24. Even though these are rare limit breaks, especially on section 23 the current almost reached the top limit multiple times. Therefore, it has to be anticipated that the addition of extra load in the form of IMC trolleybus traction and battery charging can pose problem in terms of too high current in the overhead lines. The one case of current larger than 840 [A] on section 24 again belongs to the high demand case already mentioned.

As the following sections will evaluate how successful the estimator is at predicting the amount of available power capacity for charging the IMC on-board battery, it is desired to figure out what that capacity is and if the substations can handle an extra load. The substation power demand limits have already been mentioned in table 4.4. It can be seen that in almost all cases on days 1 and 268, the substations can accommodate at least one IMC vehicle with drawing the maximal power possible, which is 500 [kW]. As rare as this power demand is, it can be assumed that there is enough power capacity which would allow two IMC vehicles to charge the maximal power of 240 [kW] and also uses the power from the overhead lines for traction purposes.

Other representative days which have been simulated do not show any bottlenecks. It makes sense as all other days can be characterized by either lower traffic on sections or lower power consumption due to reduced HVAC utilization. This makes huge difference as it consumes 43 [kW]. For this reason, the results of remaining days are presented at the end of this section for further results reference.

When looking at all the figures presented in this section so far, it can be noticed that there are moments that could potentially be problematic even at the trolleybus-only operation. These are the breaches of current limitation of overhead lines or the minimal voltage on section getting close to the bottom limit which would force the substation to disconnect the particular section from its supply. On the other hand, these are mostly infrequent occasions. The Valley-Charging approach should exactly detect these problematic spots and curtail its power demand or even completely postpone its demand for time when it is more certain to require such power from the trolley-grid.

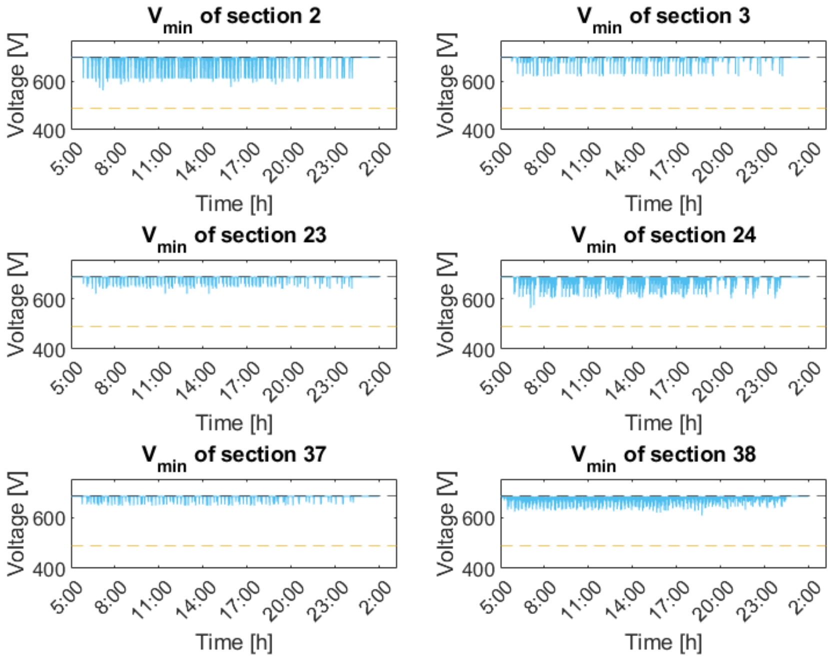


Figure 4.5: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Initial trolleybus only scenario.

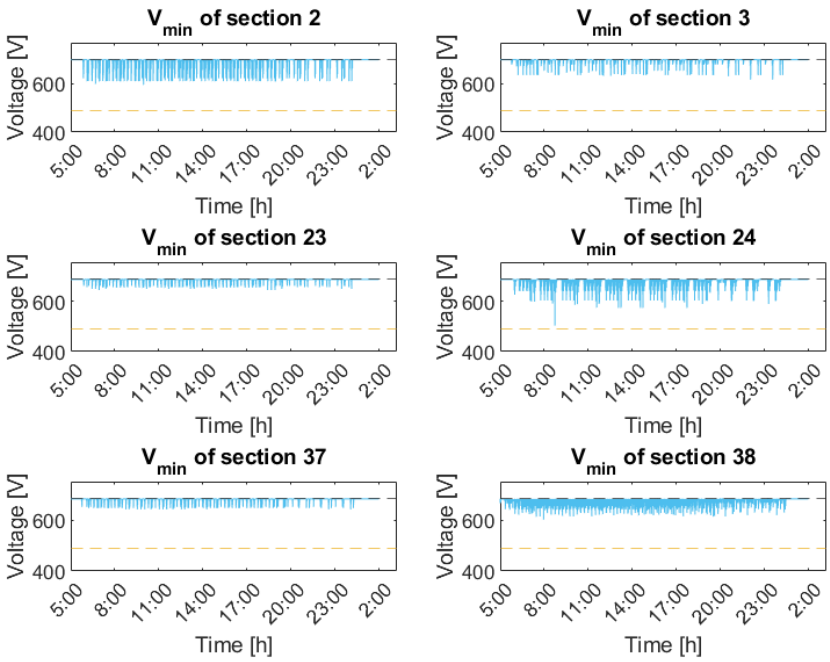


Figure 4.6: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Initial trolleybus only scenario.

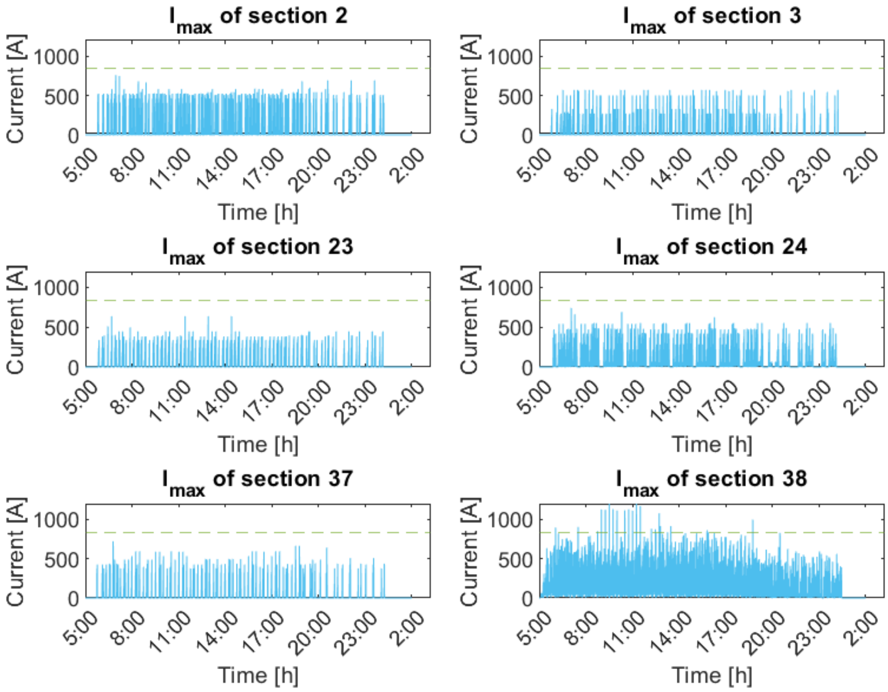


Figure 4.7: Maximal section current for each section of line 352 during **day 1**. Horizontal dashed green lines represent maximal current allowed of 840 [A]. Initial trolleybus only scenario.

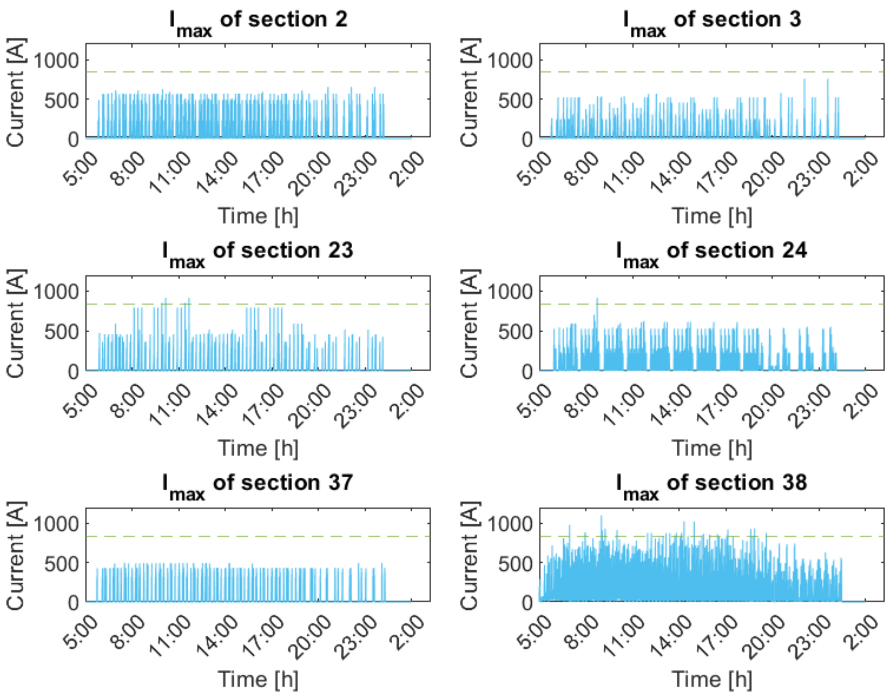


Figure 4.8: Maximal section current for each section of line 352 during **day 268**. Horizontal dashed green lines represent maximal current allowed of 840 [A]. Initial trolleybus only scenario.

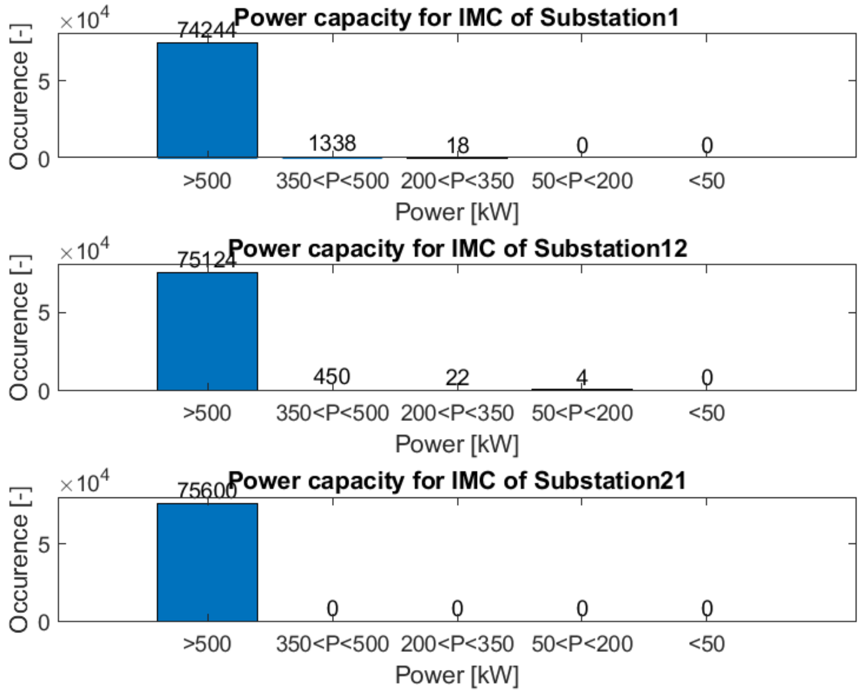


Figure 4.9: Available power capacity for IMC battery charging per substation on day **1**. Initial trolleybus only scenario.

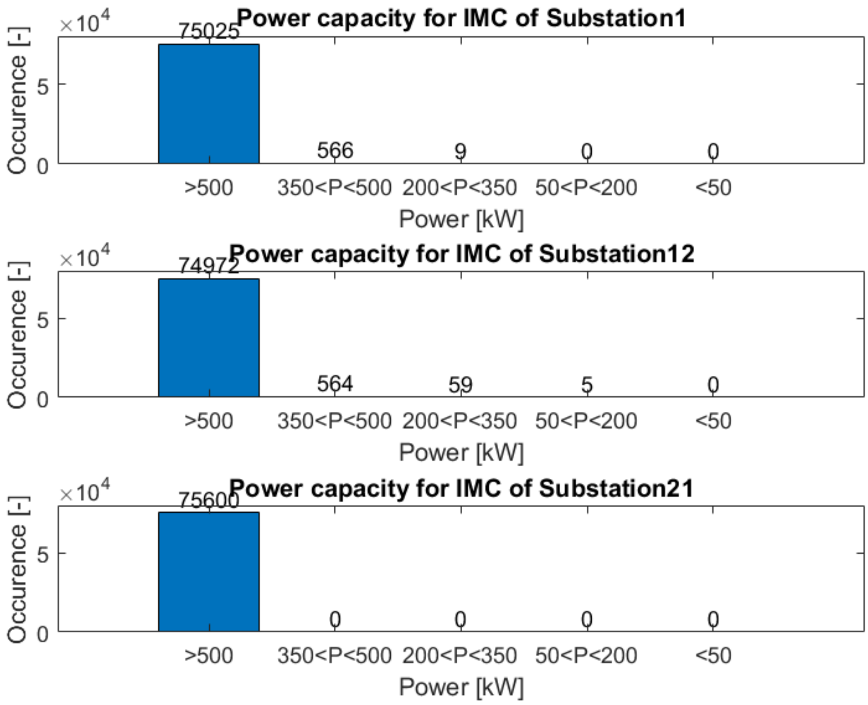
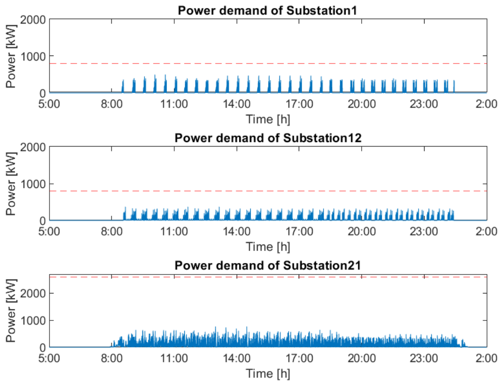
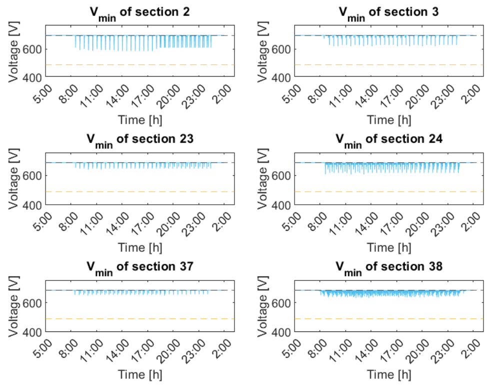


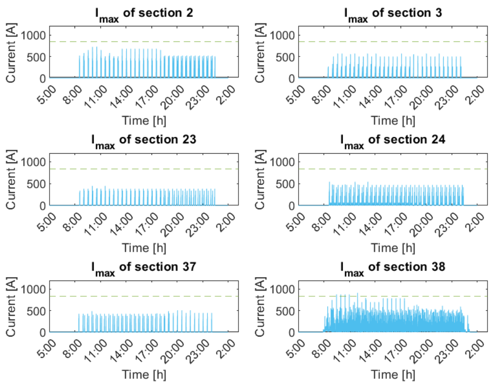
Figure 4.10: Available power capacity for IMC battery charging per substation on day **268**. Initial trolleybus only scenario.



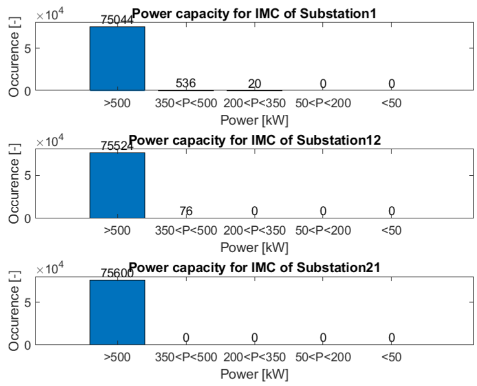
(a) Power Demand per Substation



(b) Minimal Voltage per section



(c) Maximal current per section



(d) Power Capacity

Figure 4.11: Results of initial trolleybus-only scenario of Arnhem trolley-grid **day 117**. Sections 24, 23, 2, 3, 37 and 38 and their corresponding substations included

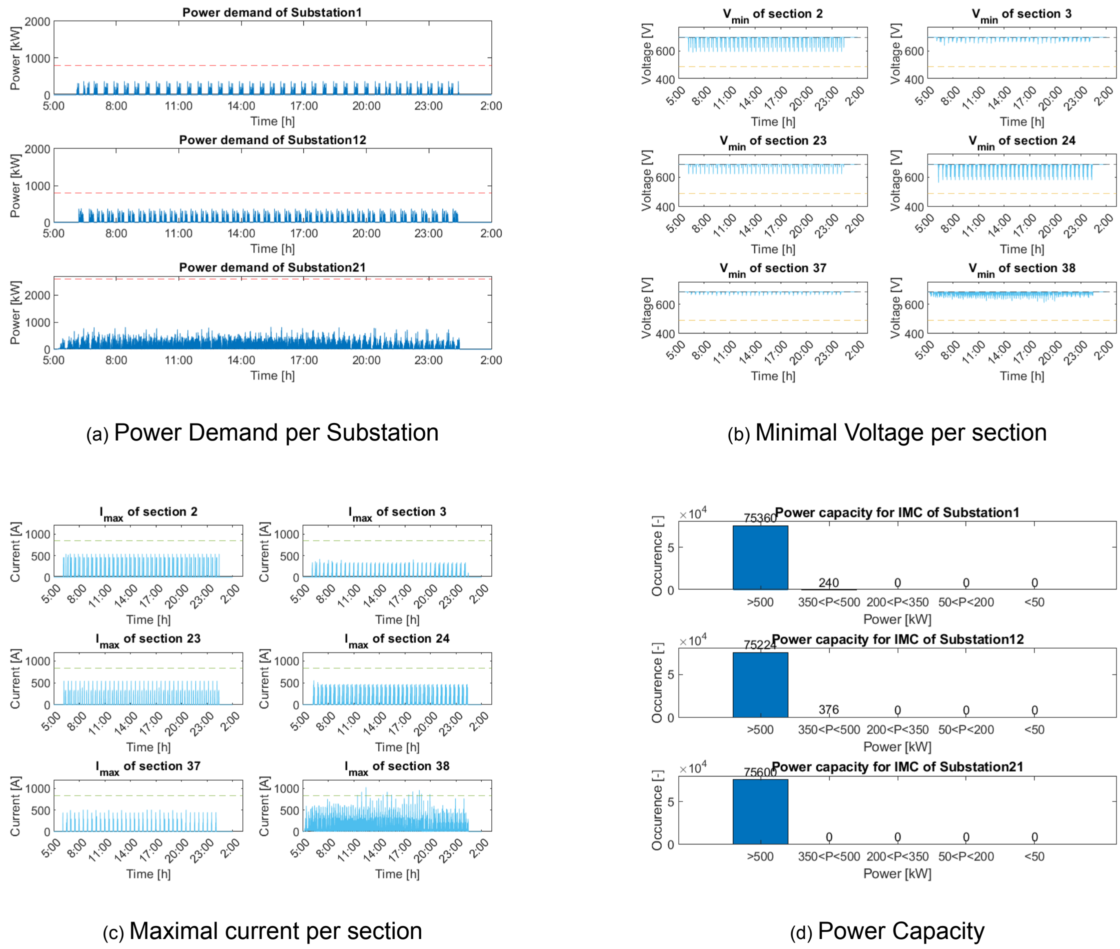
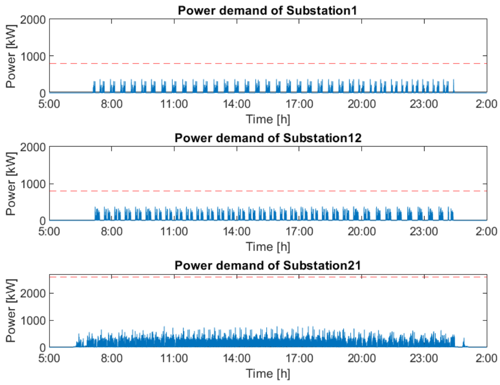
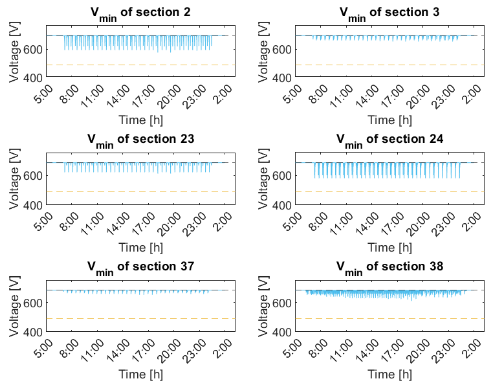


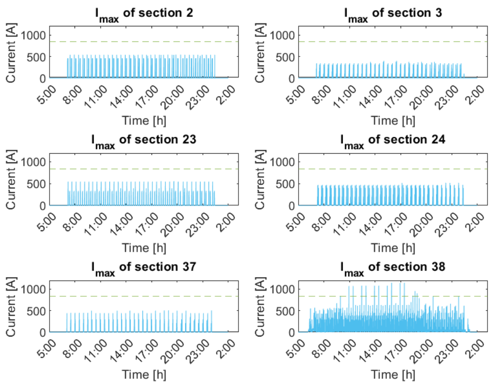
Figure 4.12: Results of initial trolleybus-only scenario of Arnhem trolley-grid **day 197**. Sections 24, 23, 2, 3, 37 and 38 and their corresponding substations included



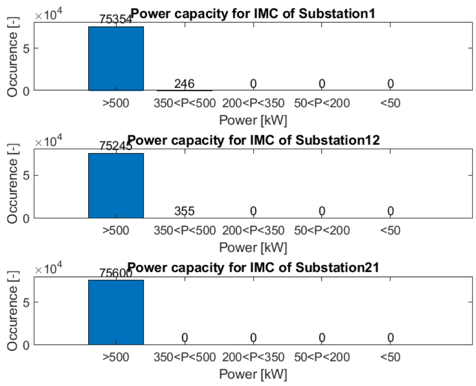
(a) Power Demand per Substation



(b) Minimal Voltage per section

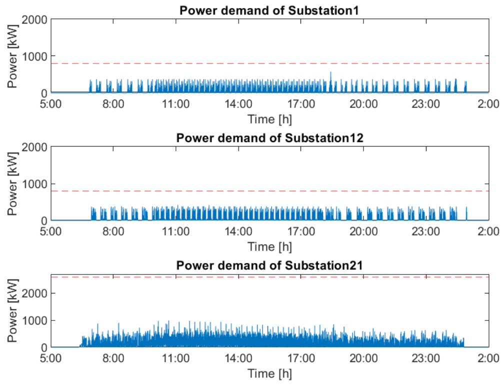


(c) Maximal current per section

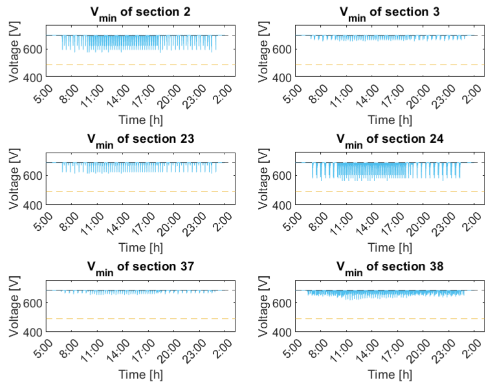


(d) Power Capacity

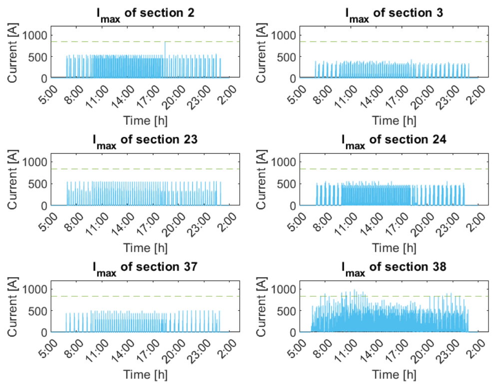
Figure 4.13: Results of initial trolleybus-only scenario of Arnhem trolley-grid **day 200**. Sections 24, 23, 2, 3, 37 and 38 and their corresponding substations included



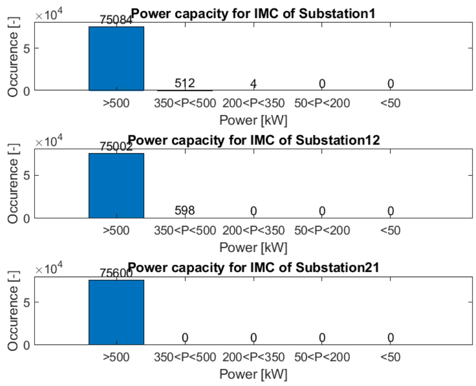
(a) Power Demand per Substation



(b) Minimal Voltage per section



(c) Maximal current per section



(d) Power Capacity

Figure 4.14: Results of initial trolleybus-only scenario of Arnhem trolley-grid **day 305**. Sections 24, 23, 2, 3, 37 and 38 and their corresponding substations included

4.3. Best Case Scenario

This section includes results of the Best Case scenario without using the estimator. When talking about the Best Case scenario, full overview of the trolley-grid is accessible for each of the vehicles. In reality, this could be achieved by installing sensors all over the trolley-grid to collect data of the motion of the vehicles, their expected behavior, etc., followed by an active communication between the vehicles which would share their measurements of voltage, current and for example their SoC in the case of IMC trolleybuses. This conditions of the trolley-grid are modelled by providing all of these data in the form of data sets during the simulation. As the vehicles are well informed, there should not be any breaches of the technical limits of the grid caused by additional demand for the IMC battery charging. Therefore, the results should provide an insight into what is the real potential of the Valley-Charging technology with no limit violations. The violations are summarized in table 4.5. The few violations are not caused by charging the on-board battery but solely by the traction power of multiple vehicles supplied by the same substation. As the trolleybuses do not charge their batteries at that time, they act as regular trolleybuses and the violations are matter of high traffic.

Table 4.5: Number of power, voltage and current limits violations per representative day. Best Case Scenario

Parameter	Day 1	Day 117	Day 197	Day 200	Day 268	Day 305
Power	20	14	3	1	15	7
Voltage	0	0	0	0	0	0
Current	152	62	51	75	99	131

Day 1

First day of the year can be characterized by high traffic of the public transport vehicles as well as high energy consumption of HVAC due to lower ambient temperatures. This makes the day very challenging as its consumption can be almost double compared to spring days. The power demand on each substation involved can be seen in figure 4.15. Generally, the power demand limit has almost never been violated for any substation, especially not for substations 12 and 21 (second two subplots of the figure). Substation 1 rarely sees minor violations of the 800 [kW], out of which the highest is a power demand of 826 [kW]. No peak above limit lasts longer than 2 [s].

The maximal current of each section is plotted in figure 4.17. Even the current sometimes goes over the allowed limit of 840 [A], most frequently on sections 2,3 and 38. The stress on substation 1 is visible from both figures that has just been described. As section 2 and 3 are rather long, the probability of meeting other vehicles on the section rises. It can be noticed that the overshoots of the limit in one plot do not necessarily correspond to the overshoots in the second plot. This is due to the fact that the power demand limit of substation is a combined limit for all the sections it feeds, whereas the current limit is exclusively affected by the operation on the particular trolley-grid section. In other words, operation of vehicles on both sections 2 and 3 is in compliance with the current limitation but the sum of their power demands and the caused transmission losses can be higher than what the substation can actually provide.

The iteration logic of this scenario with communication presented in section 3.2 works in a way that the battery charging power of all IMC vehicles is being decreased from the maximal value of 240 [kW] until all the limits of substation power demand, current and voltage are met. It can certainly happen that just the addition of extra load in the form of traction power IMC trolleybuses influences the quantities so much that even though the vehicles do not want to draw power for battery charging, the limits are still violated. In fact, all the violations of this scenario with communication have to come from just the traction power of the trolleybuses involved at that moment and not the battery charging power. With perfect communication, the vehicles lower the charging power down to 0 [kW] when the circumstances do not allow. As the traction power is not changed, the violation only comes from the traction power demand.

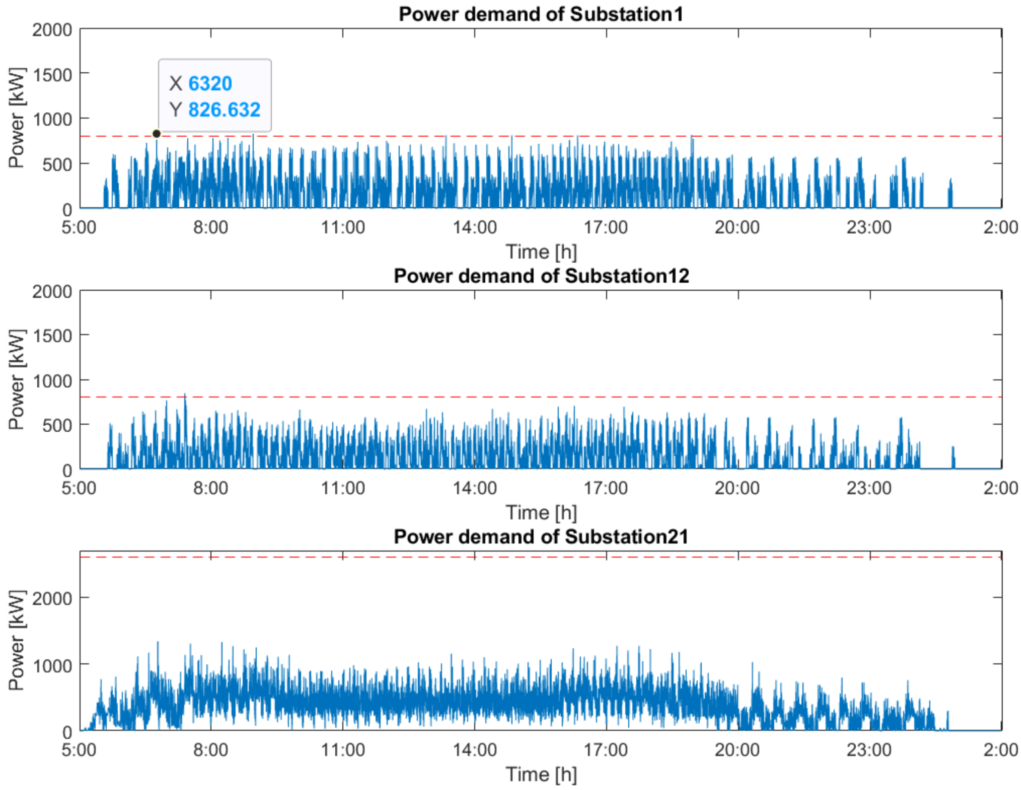


Figure 4.15: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

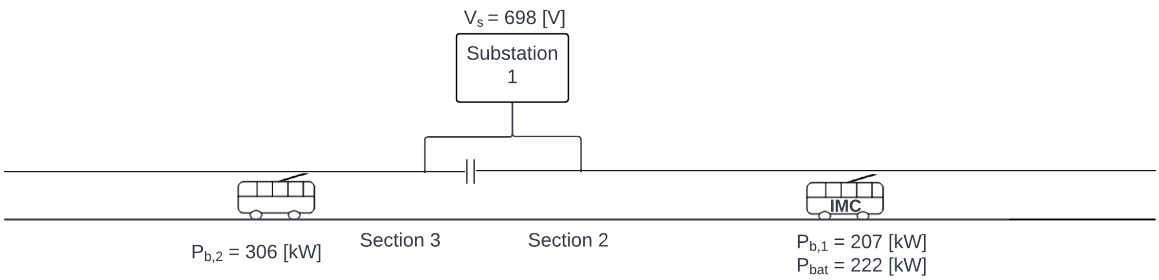


Figure 4.16: Situation of traffic on sections 2 & 3 at t=6320 when the total power demand on substation 1 was $P_{tot} = 826[kW]$

In the first subplot of figure 4.15, there is one violation of the power demand limit highlighted. A peak value of 826 [kW] occurred at substation 1 when the situation on sections 2 and 3 were as showed in figure 4.16. In this situation, there is only just one vehicle connected to each section, which one of them is an IMC trolleybus. Even though the amount of vehicles is low, the limit of power demand was broken. The available power the substation can provide at this time had been calculated just with the trolleybus on section 3 drawing 306 [kW] before the IMC vehicle was added. It already counts with 10% of transmission losses. However, this situation resulted in transmission losses higher than 10% of the total bus power demand of more than 92 [kW], from which 83 [kW] was from section 2.

The limit break in the previous example came from an input in the form of power capacity available which counts with 10% transmission losses. Neither a violation of current limit, nor a voltage limit can happen with power for on-board battery charging being drawn. Figure 4.18 shows a situation of the

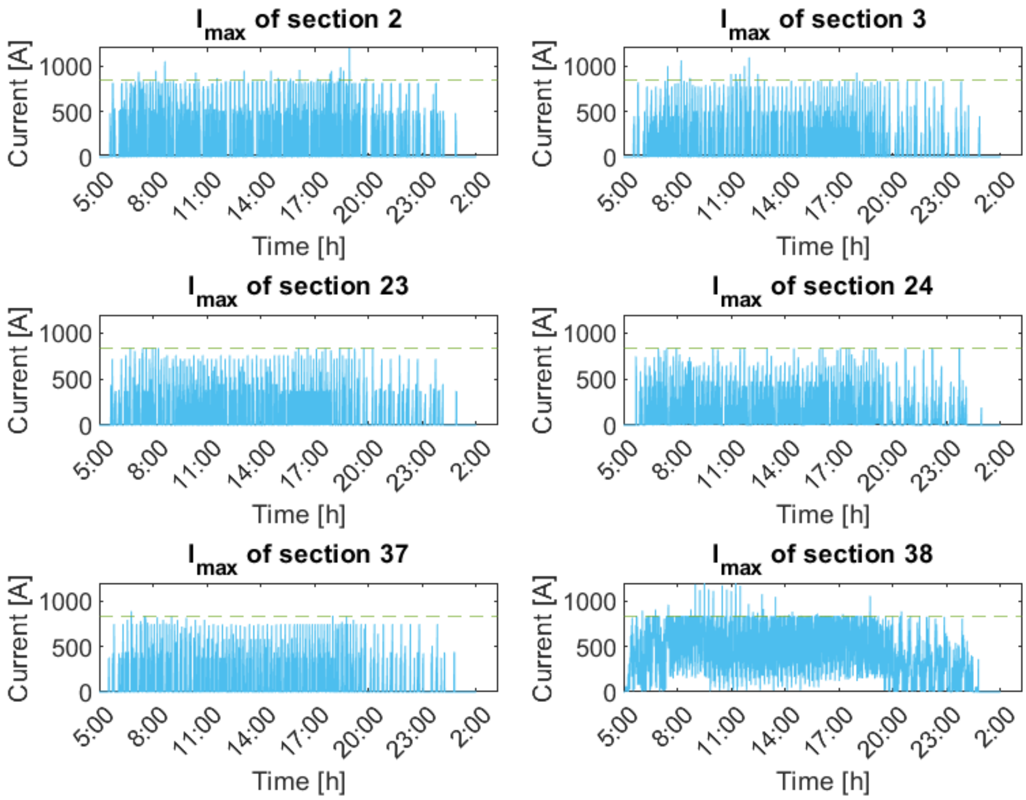


Figure 4.17: Maximal current on each section of line 352 route during **day 1**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

largest value of current of 1202 [A] during day 1. The traffic on section 2 consisted of 3 vehicles, where one of them was IMC. It has to be noted that the IMC trolleybus and trolleybus number 3 were at the end of acceleration based on their traction power demands combined for 566 [kW]. When the last vehicles' traction power is added, the trolleybuses require almost 660 [kW] in total just to get moving. After the iterations, the battery charging power was set to be $P_{bat,1} = 0[kW]$. Not even failing to charge the on-board battery prevented the current from exceeding the limit by approx. 350 [A]. From the perspective of power demand, the substation had to provide 815 [kW] (including the transmission losses). This is a proof that just by adding another trolleybus load to the public transport network, the technical parameters do not have to suffice this purpose even without charging the battery. The voltage of the trolleybuses was not putting the substation into jeopardy, however, the lowest value of 528 [V] at the very last trolleybus is coming close to the allowed voltage and another vehicle would definitely break it. From figure 4.19, it can be seen that voltage was no problem throughout day 1.

With regards to the SoC of the IMC trolleybuses captured in figure 4.20, almost the whole operational area between the limits of 90% and 20% was used. Mainly due to the fact that day 1 is very demanding on the energy consumption due to HVAC. The rising slope of the curve representing charging of the battery does not stop. That is because charging was not stopped at the A station to help the SoC recover as much as possible. Even though the upper limit is reached already at the A station, which means that the route from A to W wastes the potential of driving under the overhead line, it seemed crucial to have full SoC to make the IMC line operable.

Day 117

During day 117, basically the same phenomena already spotted and explained for the previous day 1 can be also witnessed. This day should be the most relaxed day of all the six as it is both low traffic and

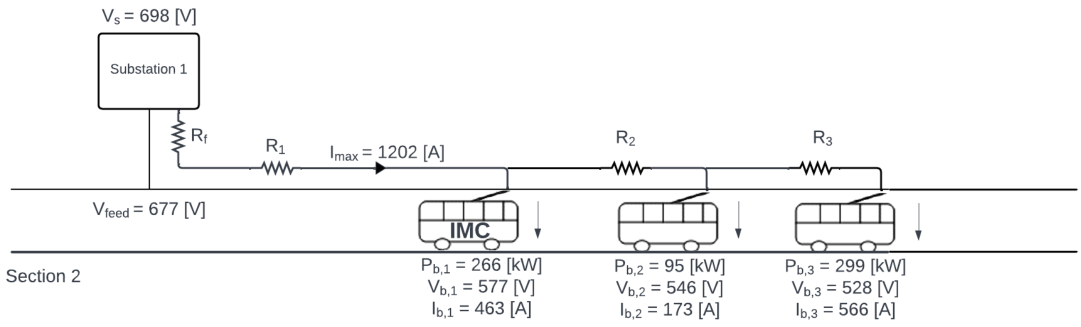


Figure 4.18: Situation on section 2 at t=50178 (approx. 7pm) on day 1 when the limit of maximal current in the overhead lines of 840 [A] was violated. Two regular trolleybuses and one IMC vehicle connected. Direction of the vehicles does not correspond to their real movement.

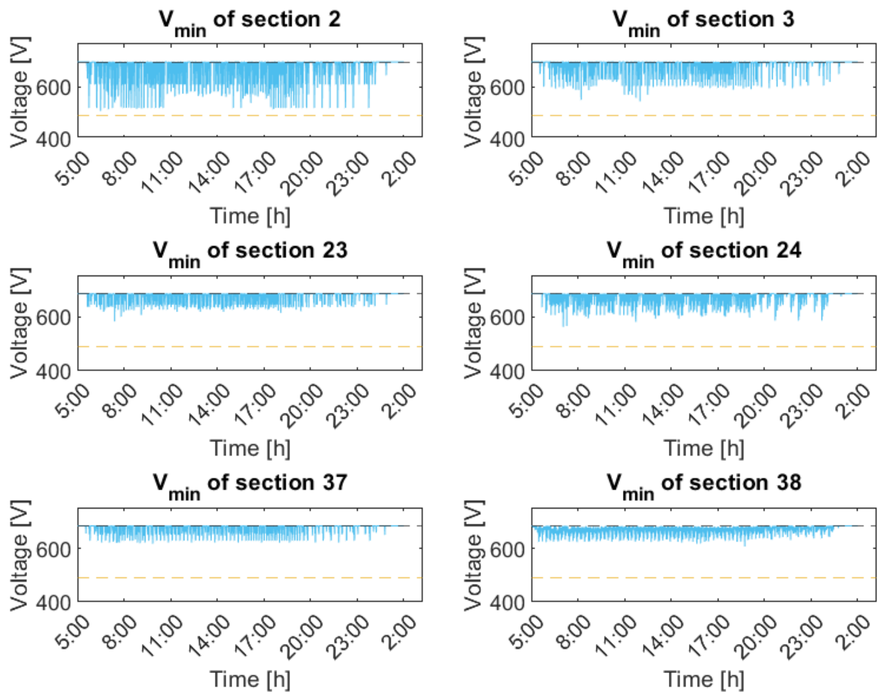


Figure 4.19: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

low HVAC consumption due to spring season. Except for currents in the overhead lines of inappropriate values, adding this IMC line is acceptable for this day. The largest difference is in figure 4.24. The significance of power consumption for heating and cooling the cabin of the vehicle is now transferred into much better SoC levels compared to day 1.

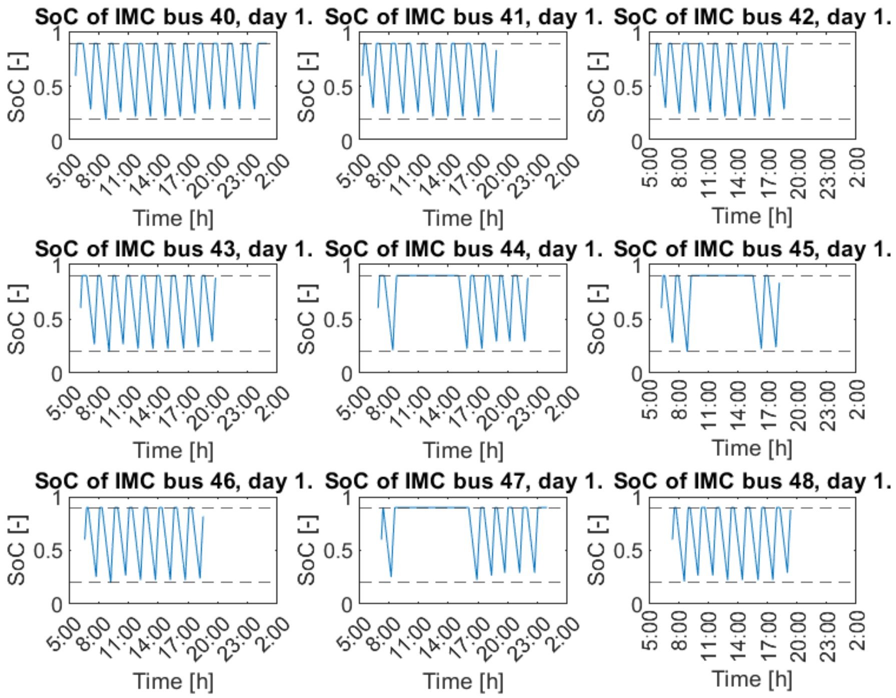


Figure 4.20: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 1**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

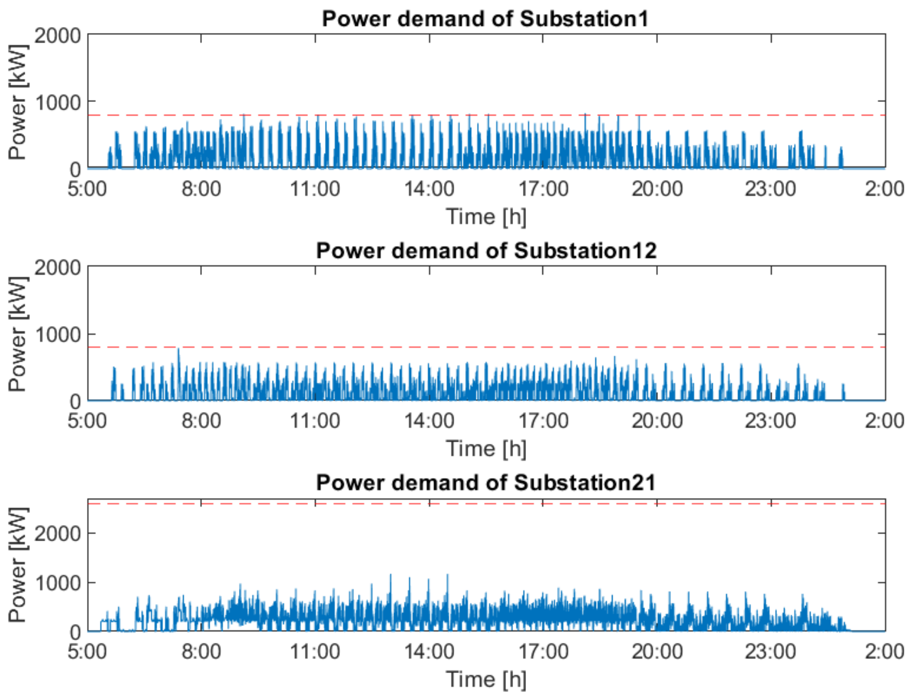


Figure 4.21: Substation power demand during **day 117**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

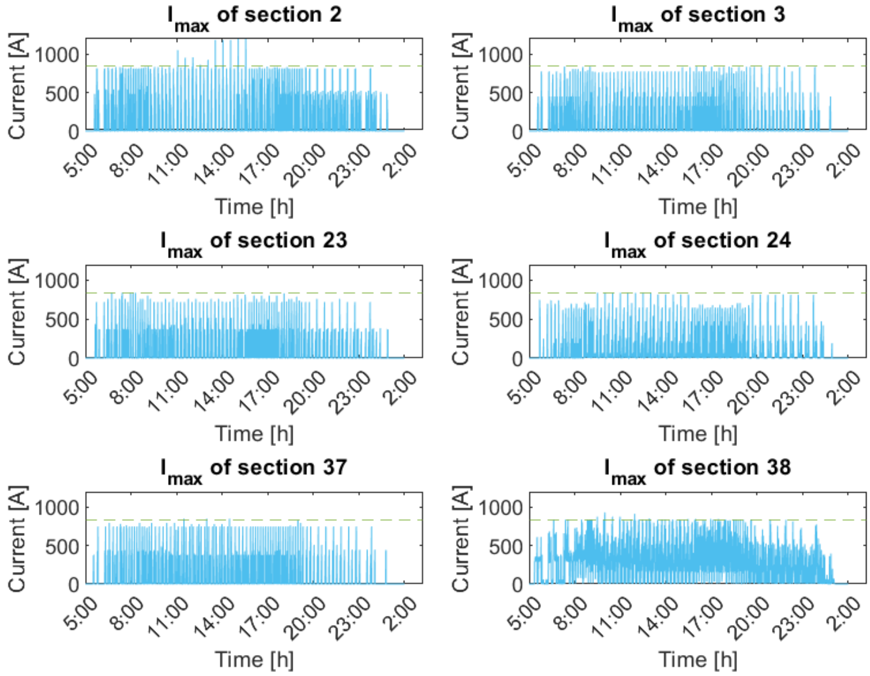


Figure 4.22: Maximal current on each section of line 352 route during **day 117**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

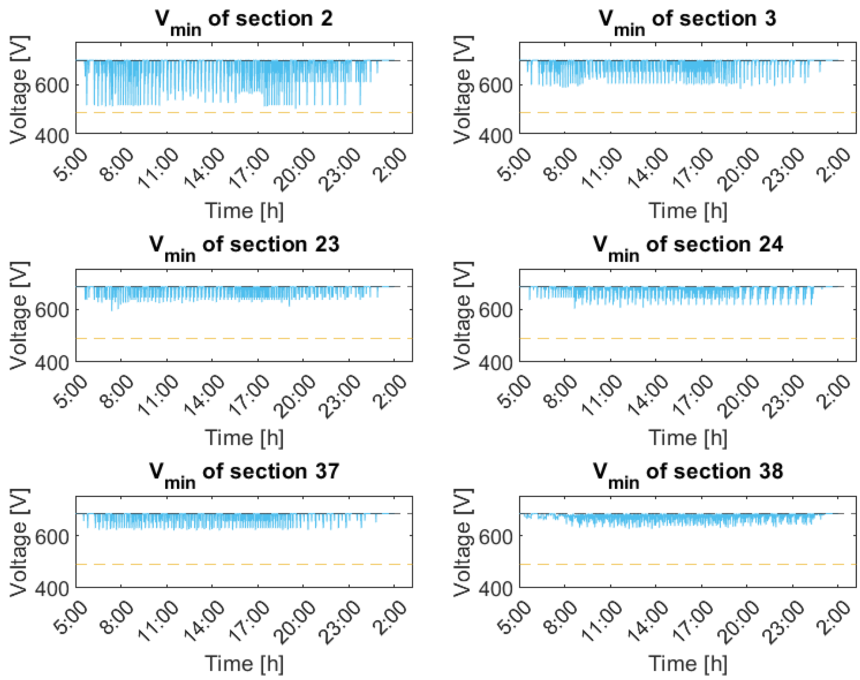


Figure 4.23: Minimal section voltage for each section of line 352 during **day 117**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

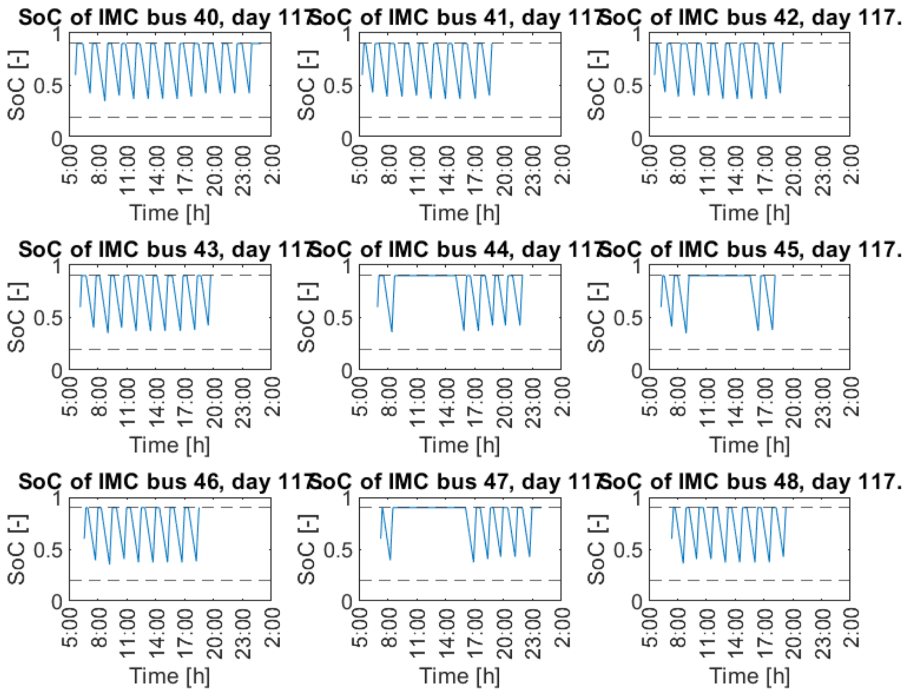


Figure 4.24: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 117**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

Day 197

Apart from the situations when the current and power demand on substation have higher values than allowed, day 197 brought a violation of the voltage limit. The value is highlighted in figure 4.27. As the voltage dropped below 490 [V] down to 470 [V], the substation would disconnect the section from its supply to save itself from breaking down. It has already been mentioned that the voltage on section 2 is getting close to the limit and another vehicle on the line would break it. However, it is not the case now as even less vehicles than in the example of figure 4.18 pushed the grid to the edge. The section only housed two vehicles, one IMC trolleybus and one regular trolleybus (figure 4.28). Although the power demand for traction is not unreasonably high and the IMC vehicle does not charge its battery, the combination of these powers and the position of both of the vehicles caused such voltage drop. Both vehicles are placed at the very end of the section on the side further away from the feed-in point. The fact that they are almost 1200 [m] away from there means the sum of their currents of 1067 [A] has to travel very long way through the resistance of the overhead lines resulting in massive losses of 238 [kW]. Even though this situation lasts shortly as one bus has just entered the section and the other is on its way out, unlike with violating the current limitation where it causes overheating of the overhead lines over time, time does not matter to the voltage limit and is problematic even for one second.

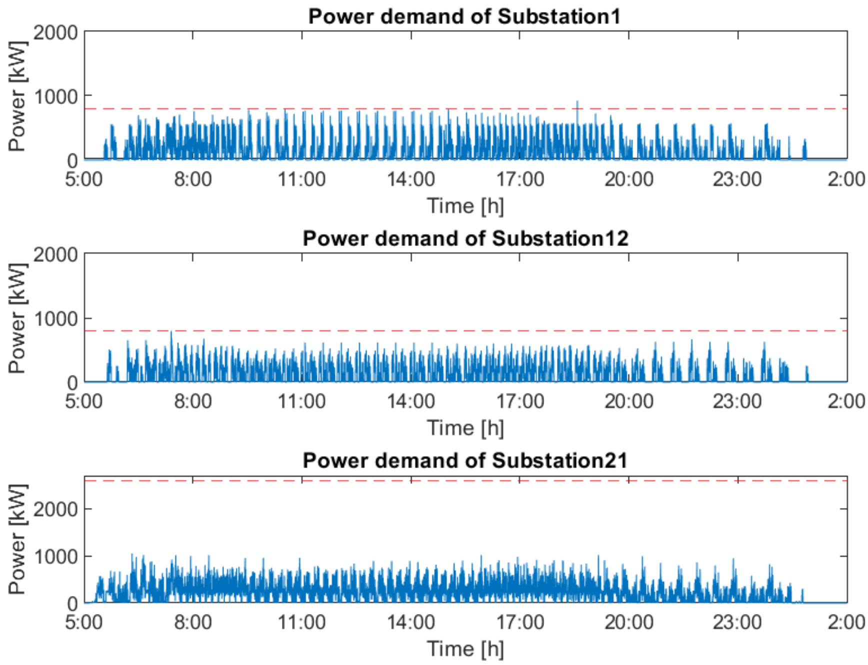


Figure 4.25: Substation power demand during **day 197**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

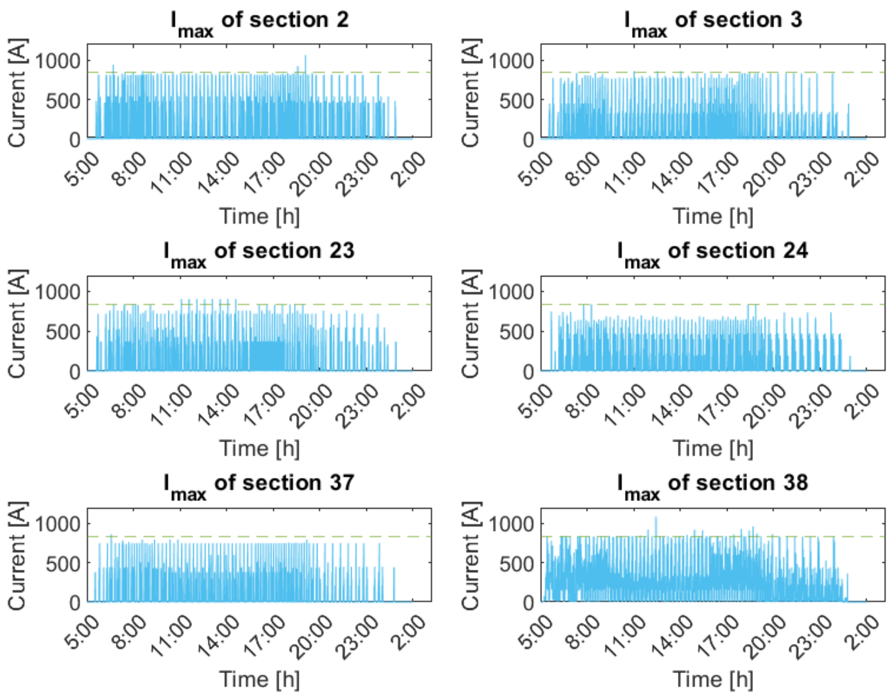


Figure 4.26: Maximal current on each section of line 352 route during **day 197**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

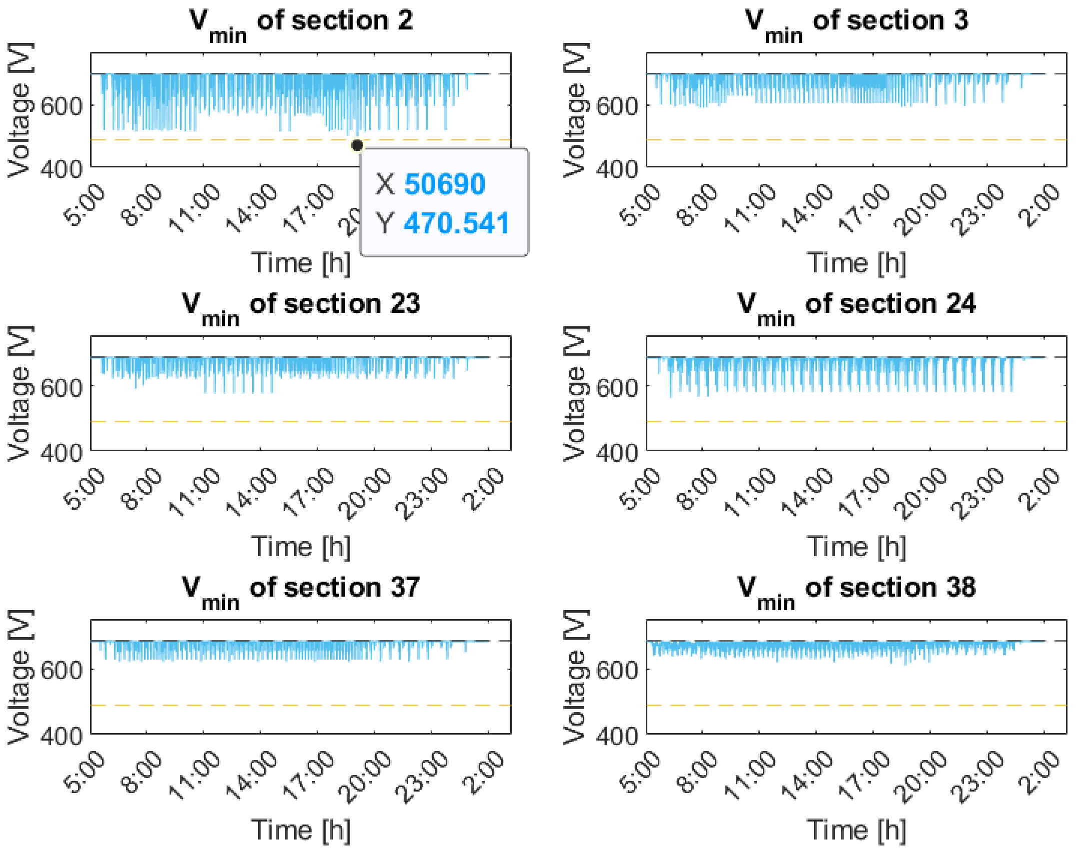


Figure 4.27: Minimal section voltage for each section of line 352 during **day 197**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

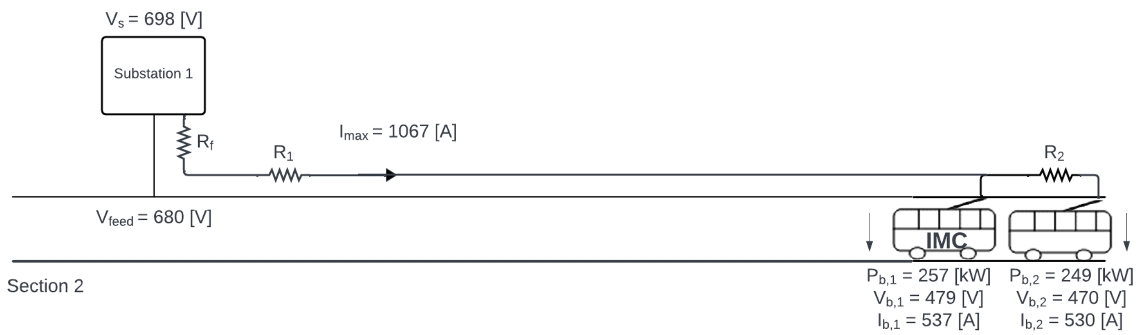


Figure 4.28: Situation on section 2 at t=50690 (approx. 7pm) on day 197 when the limit of minimal voltage of 490 [V] was violated. One regular trolleybus and one IMC vehicle connected. Direction of the vehicles does not correspond to their real movement.

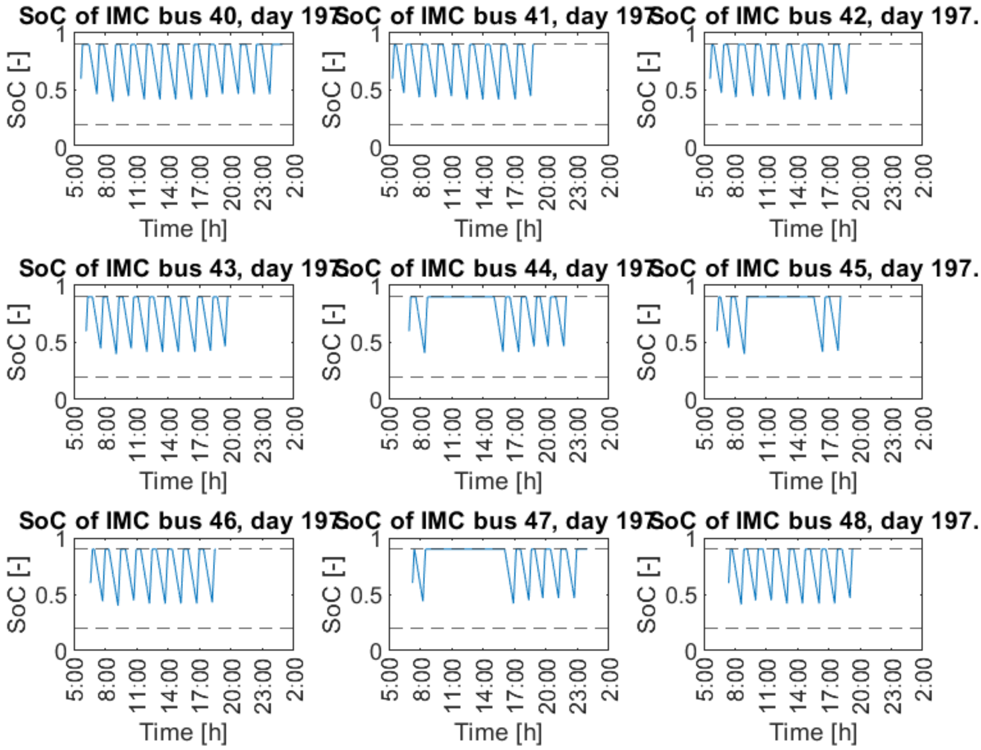


Figure 4.29: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 197**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

Day 200

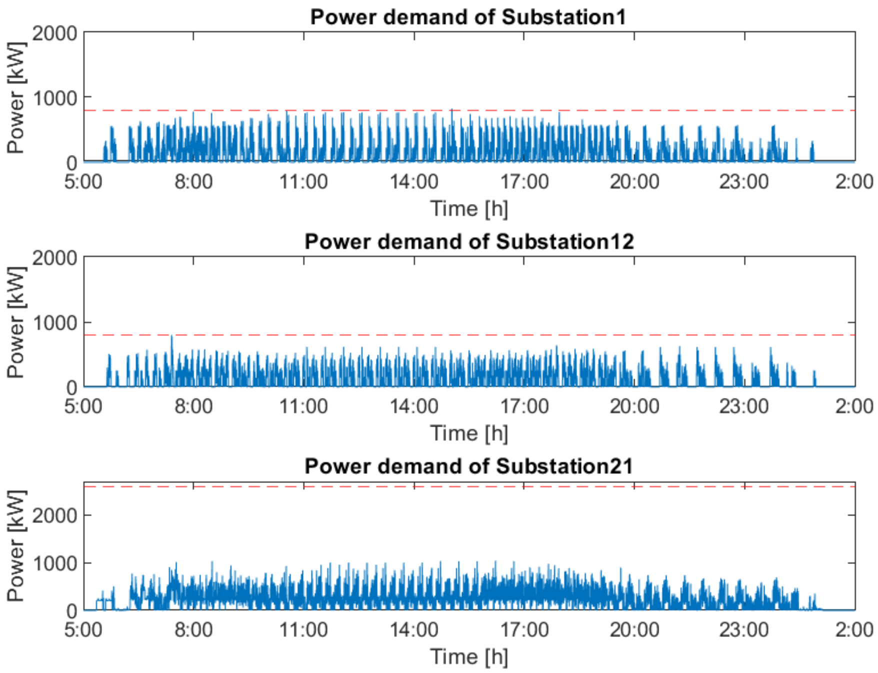


Figure 4.30: Substation power demand during **day 200**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

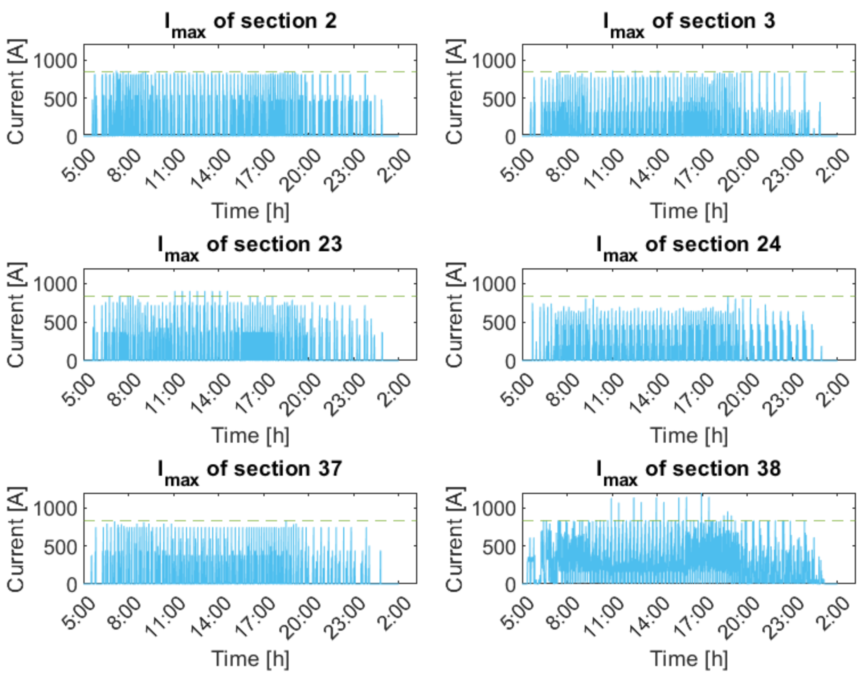


Figure 4.31: Maximal current on each section of line 352 route during **day 200**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

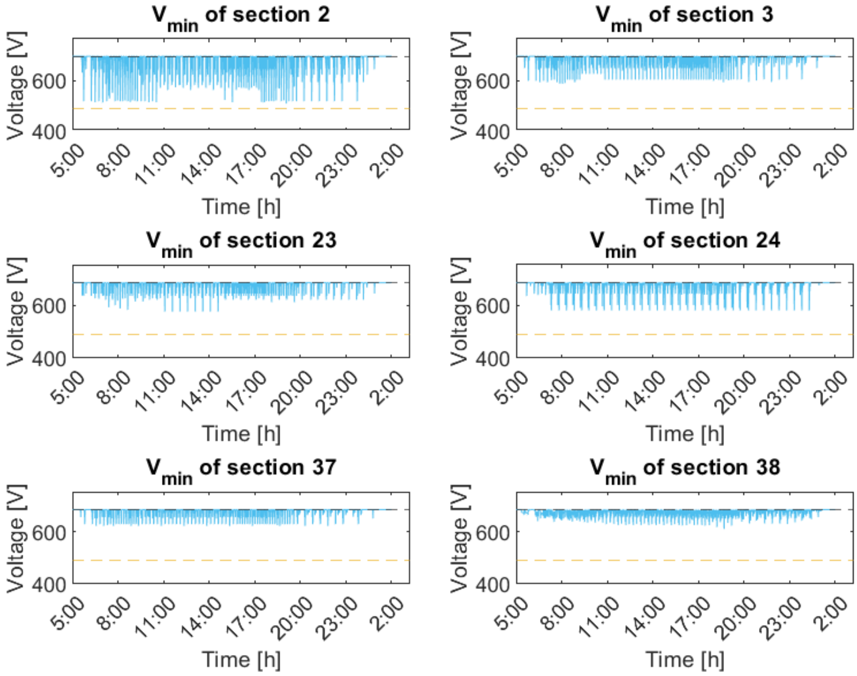


Figure 4.32: Minimal section voltage for each section of line 352 during **day 200**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

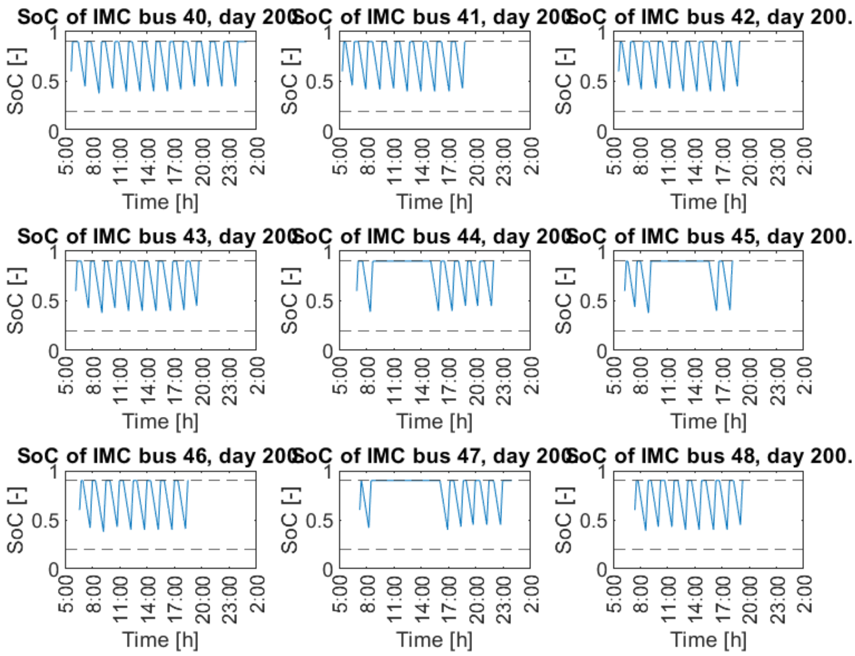


Figure 4.33: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 200**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

Day 268

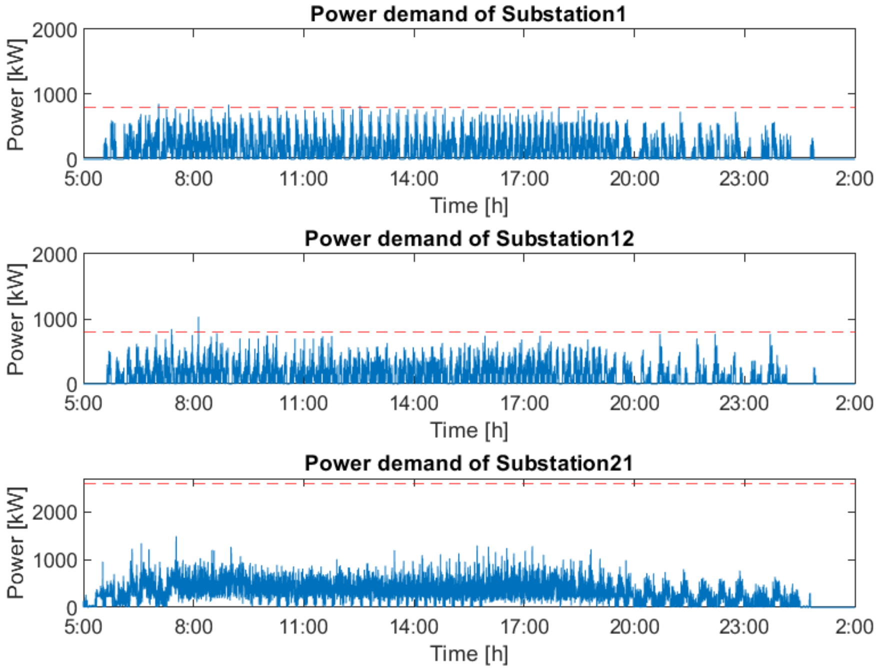


Figure 4.34: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

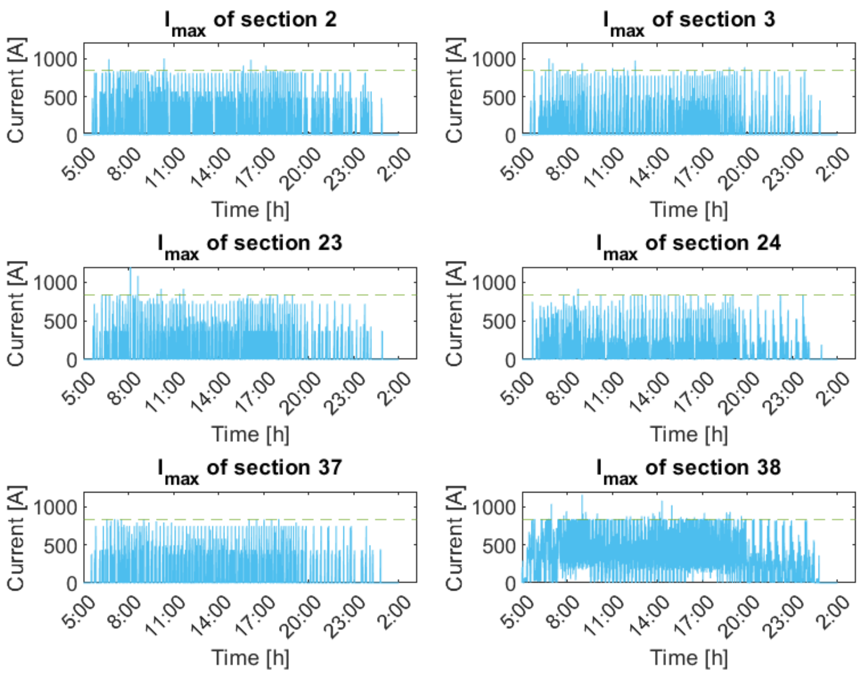


Figure 4.35: Maximal current on each section of line 352 route during **day 268**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

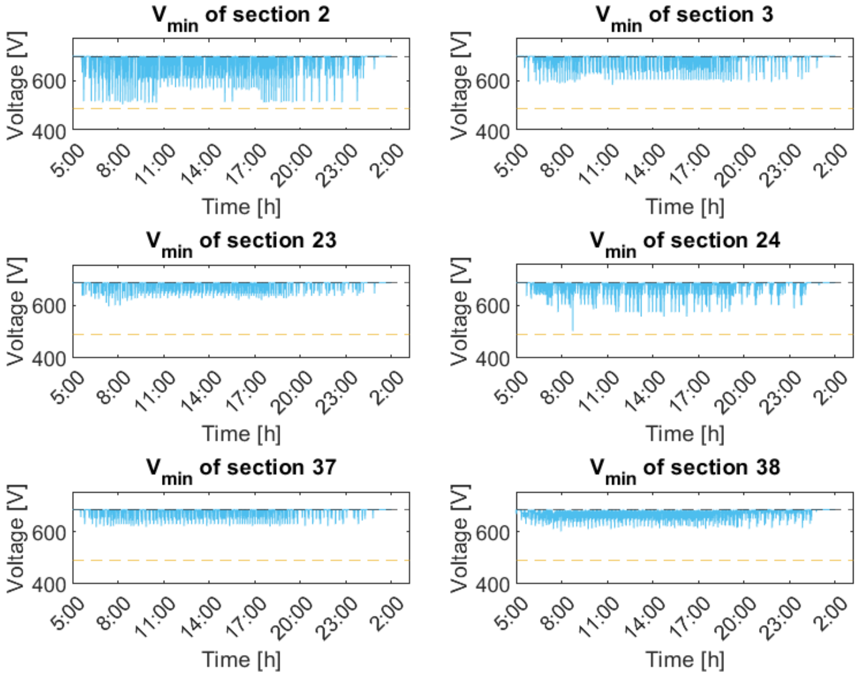


Figure 4.36: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

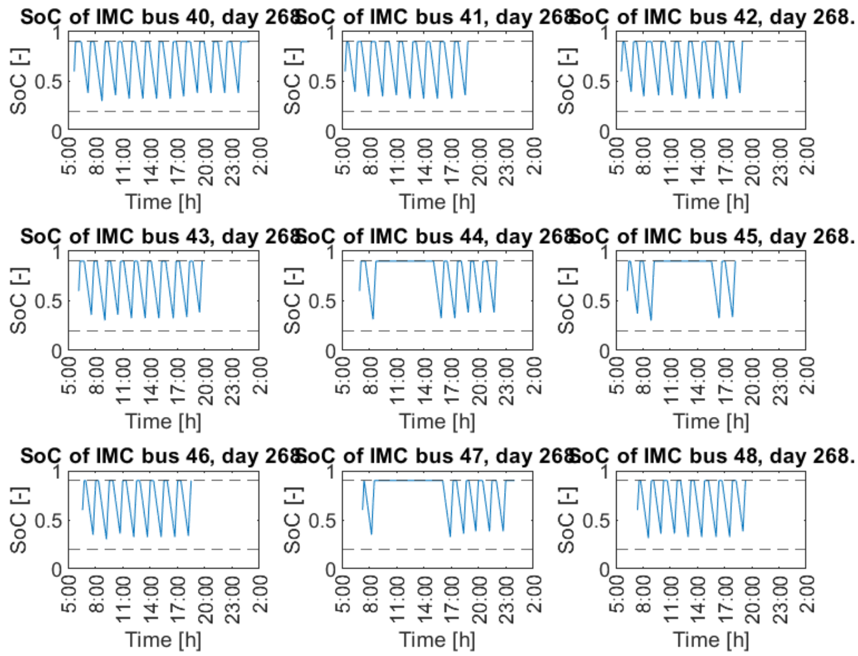


Figure 4.37: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 268**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

Day 305

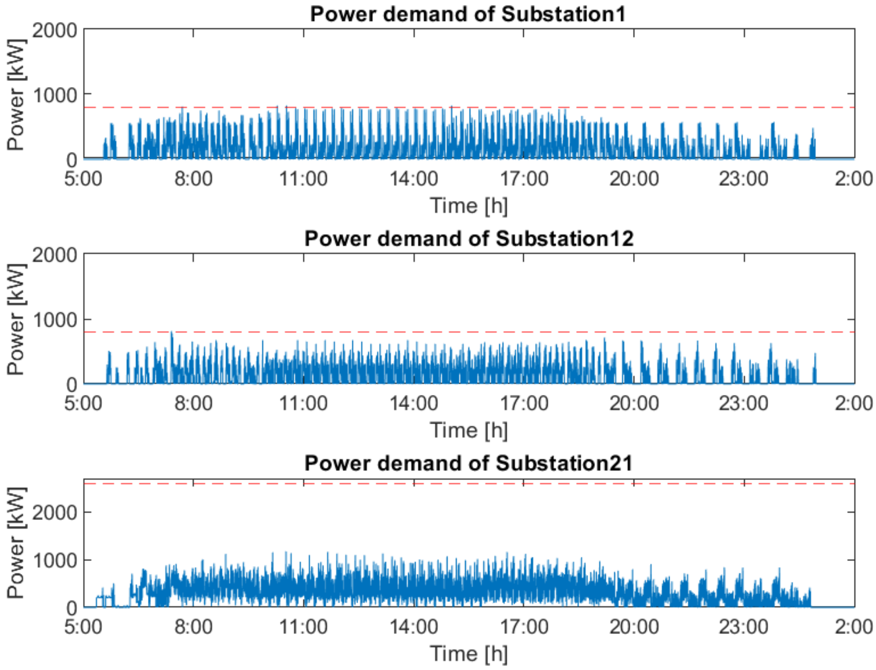


Figure 4.38: Substation power demand during **day 305**. Horizontal dashed red lines represent power demand limit of the substation. Best case scenario.

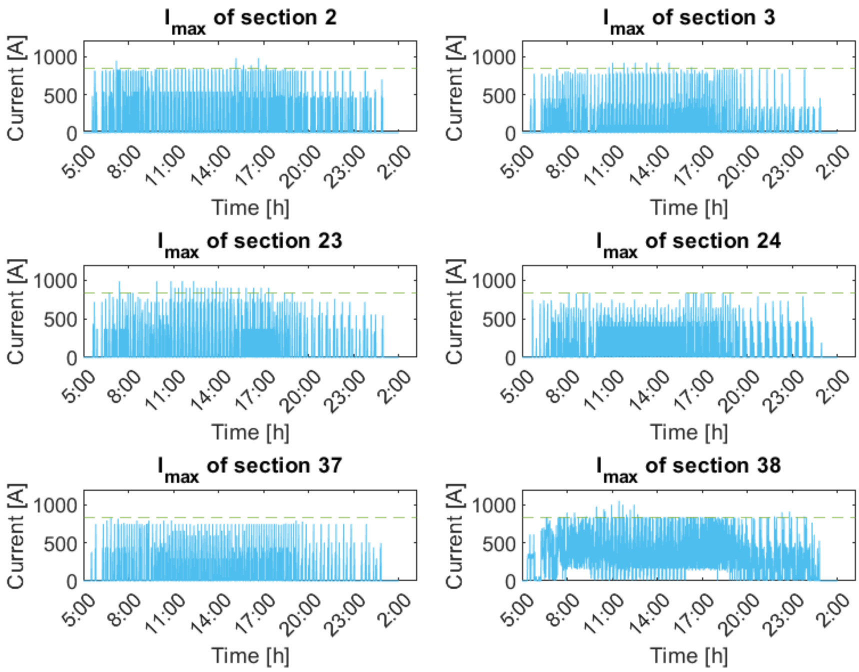


Figure 4.39: Maximal current on each section of line 352 route during **day 305**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Best case scenario.

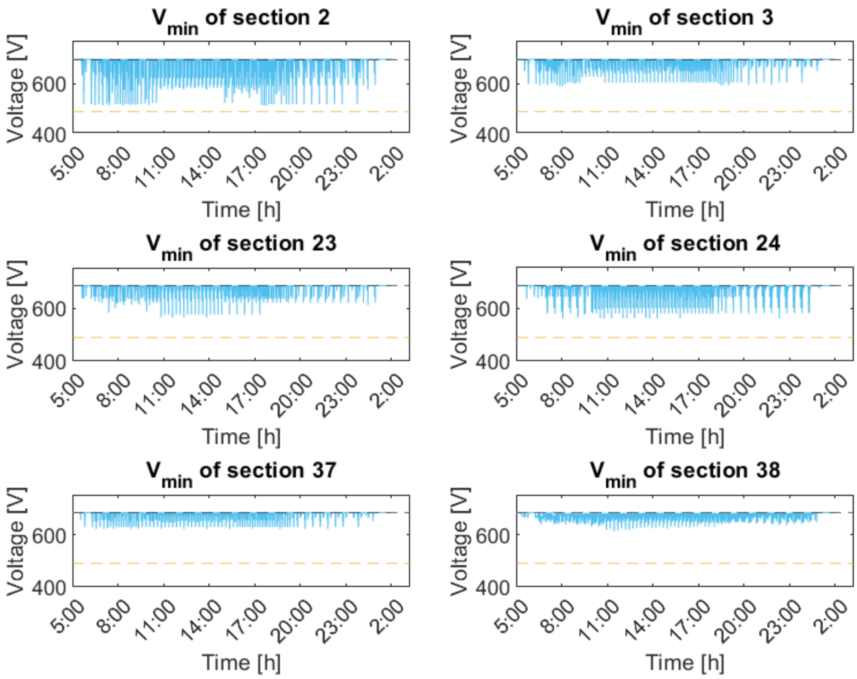


Figure 4.40: Minimal section voltage for each section of line 352 during **day 305**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Best case scenario.

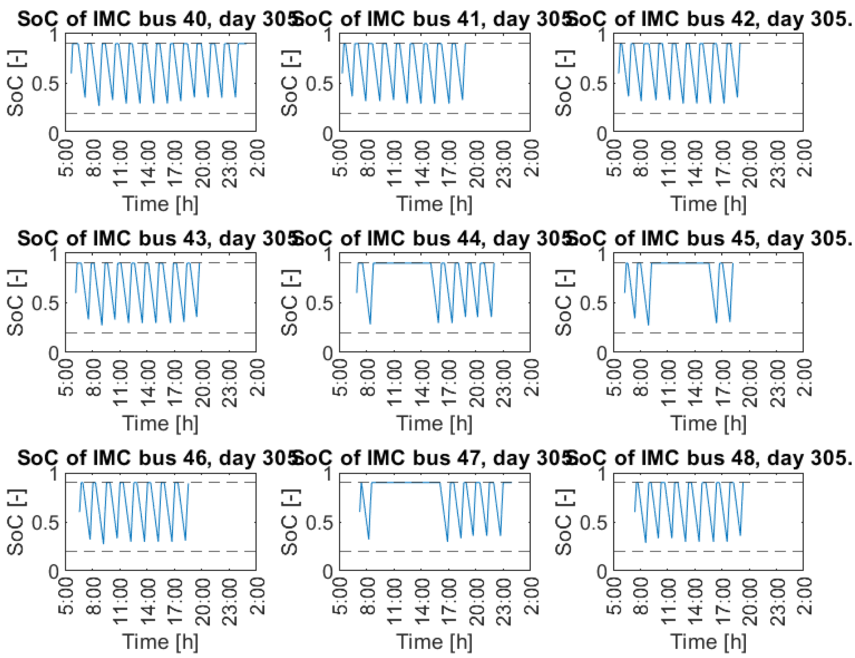


Figure 4.41: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 305**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Best case scenario.

4.3.1. Energy collected

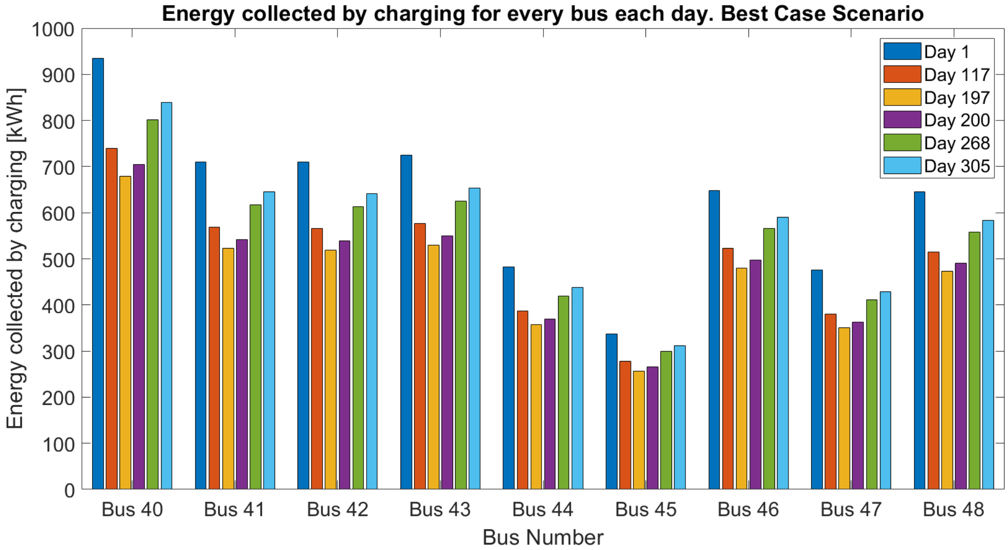


Figure 4.42: Energy collected by every bus each representative day of the year. Best case scenario.

As the IMC vehicles require power to charge their battery, an interesting parameter to follow is the amount of energy collected from the overhead lines. Figure 4.42 depicts it for every IMC trolleybus of line 352. The six separate columns for every bus represent the days which are being simulated. The previously presented plots can help to understand this bar plot better. It can be seen that day 1 (blue column) always stands out. The high consumption during winter gives space to charge for longer time before the maximal SoC is reached. It can be seen from figure 4.20 which uses the most of the area between 20% and 90% SoC. After day 1, days 268 and 305 also show high amount of energy picked up compared to the other where the energy consumption is not high and not that much charging power is needed. One can also note that some of the buses collect more energy than the other buses, which is especially the case of bus 40. The reason for that is bus 40 is making the most round trips on line 352. On the other hand, the schedules of buses 44, 45, 47 consist of only some trips on line 352 especially during peak hours in the morning and in the late afternoon/evening. In the meantime, they provide service for different non-IMC lines within the Arnhem trolley-grid. For the purpose of this thesis, it is assumed that for the other lines they operate as regular trolleybuses without depleting their on-board battery. That is the long period of constant maximal SoC in all SoC plots already shown of these buses. On top of that, bus 45 has the shortest operation time resulting in the lowest energy collected.

4.4. Estimator Versions

The previous Valley-Charging results expected there was a way of communication between vehicles, substations and sensors of technical parameters such as current in the overhead lines. However, this is not the case of today's trolley-grids. Following simulation results will use set of conditions based on on-board measurements of for example current and voltage, called the estimator, to get the closest prediction of what is currently the available power capacity for charging the IMC on-board battery. The fact that only 6 representative days of the year were simulated enabled to reflect on the results and continually improve the performance of the estimator to achieve more accurate predictions. For this reason, several sets of results will be presented here, each set corresponding to one estimator version.

4.4.1. Estimator V1 - Voltage, Current, Position Constraints for 1 Vehicle

The first version of the estimator of available power capacity for charging the on-board battery uses measurements of bus line voltage, bus current and also GPS location to find out the exact position of the vehicle on the section. The first decision branch takes care of the 50 [m] before the vehicle is about to exit the section and 50 [m] after it enters the next one. Charging $P_{\text{safe}} = 50[kW]$ when 50 [m] away from a section switch helps to fight unwanted circumstances like in the situation showed on day 197 in best case scenario (figure 4.28) where two vehicles required too much power and would collapse the grid. Anywhere else on the sections, the estimator evaluates the measurement of bus current to compare it with I_σ to determine if the vehicle is alone on the section or whether there are other vehicles connected also. The $N = 1$ case then uses the location of the trolleybus, or more precisely its distance from the feeder cable to find a corresponding value of $P_{\mathrm{cap,single}}$ representing the maximal power demand that can be drawn at that particular position in order not to brake voltage, current and transmission loss limitations (section 3.5). The $N > 1$ case has to use the historical data of relationship between the bus voltage V_{b} and available power capacity P_{av} (section 3.4). Together with the level of confidence K to be set at 95%, they lead to a value of Ψ which occurred in 95% of the cases. All final values of Ψ are then checked with the limit of the IMC500 technology as these values have to within 240 [kW].

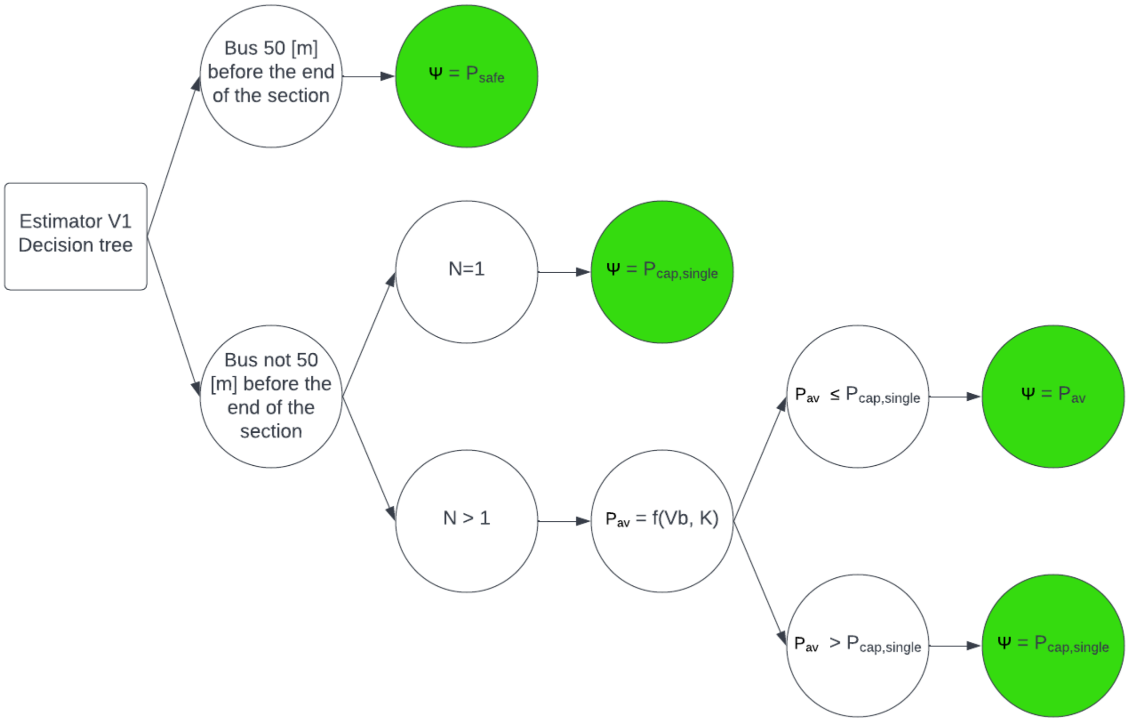


Figure 4.43: Decision tree of the first version of the estimator. Green circles represent final decision in the tree

Generally, the simple version of estimator was not enough to accurately predict the situation on the section level nor on the substation level. Violations of all parameters followed occurred, namely power demand on substation level, voltage and line current. The summary of their amount per day can be inspected in table 4.6.

Table 4.6: Number of power, voltage and current limits violations per representative day. First version of estimator based on voltage and current measurements and power cap for one vehicle on the section

Parameter	Day 1	Day 117	Day 197	Day 200	Day 268	Day 305
Power	745	708	495	525	682	728
Voltage	14	10	9	9	9	13
Current	2890	2169	2035	2115	2557	2665

The values in the table above are cumulative values for all the 9 IMC trolleybuses operating line 352. Also, the failures are not mutually exclusive. When a current limitation was broken, it means power limitation could have been broken, too. It means the sum of failures in one column for one day is not relevant. When comparing the simulated days between each other, a pattern emerges again.

The highest number of limit breaks happen during the most busy days and during the most energy demanding ones. An interesting phenomena that already showed up during the Best Case scenario was proved here and that is the current in the overhead lines being the most problematic of all. On the other hands, it can be claimed that in terms of voltage the estimator did well.

Day 1

From the power demand curves in figure 4.44, it is obvious that substation 1 failed to appropriately accommodate the extra load. Vast majority of cases when power demand overshot the 800 [kW] limit happened just there. The time step with the power demand of 1054 [kW], which is also highlighted in figure 4.44, was not an issue during the Best Case scenario where substation 1 only had to provide 642 [kW]. After closer analysis it was found out that this number is only comprising the total bus power demand of two trolleybuses of 512 [kW] and the rest are transmission losses of approx. 130 [kW]. It is then evident that the iterative approach based on communication in Best Case scenario decided not to charge at all as it would cause violation of any of the limits. This is exactly the desired action which the first version of estimator failed to take and suggested the IMC trolleybus to charge.

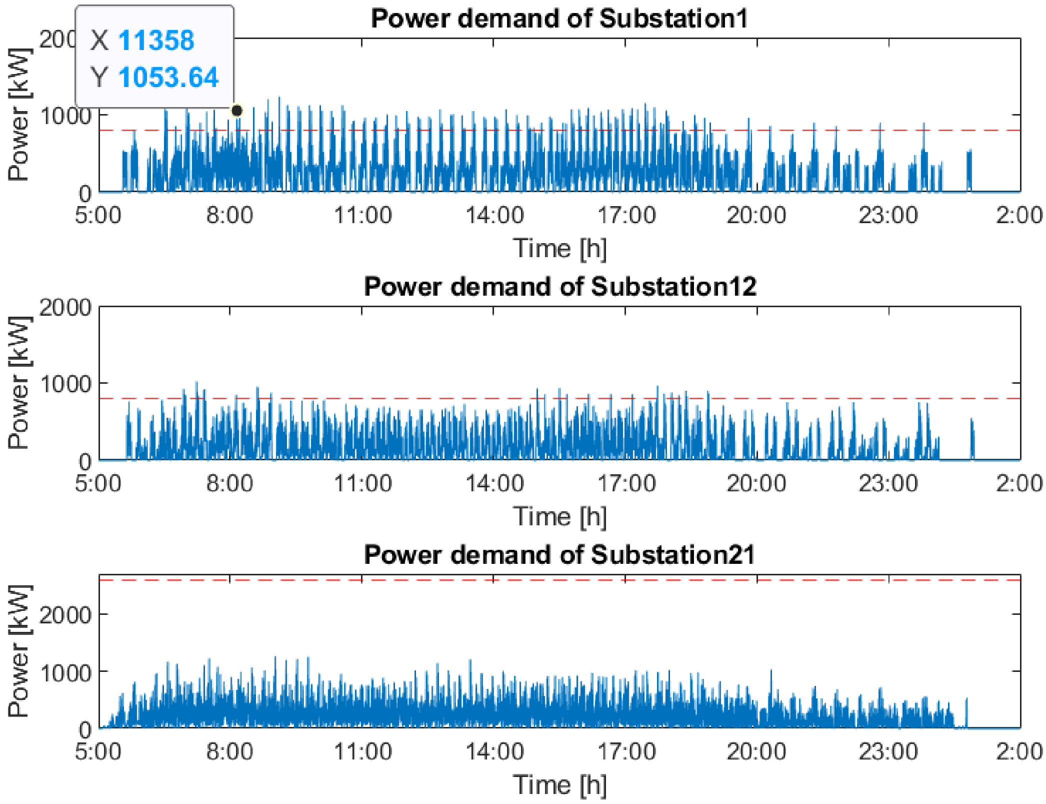


Figure 4.44: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 Scenario

If we go through the decision path the first version of the estimator took in this case, a way to improve the next version can be found. The IMC vehicle was not just entering the section, its position was somewhat 900 [m] away from the feeder cable (as well as the regular trolleybus), so there was no reason to take the safe charging power. Based on the calculated value of I_σ and the measured value of current, the estimator could determine the traffic on the section. It is necessary to mention that the estimator evaluated the parameters at $t = 11356$, that is 2 time steps before this power demand occurred. The current values thus does not correspond to the actual power demand highlighted in the figure.

$$I_b = 432[A] \mid I_\sigma = 403[A]$$

$$432\,[A] - 403\,[A] > 0.5\,[A] \quad \rightarrow \text{More vehicles connected on the section}$$

As the difference between the two current values is rather large, it was correctly assumed that the IMC vehicle is not alone on the section. In the next step, available power capacity is predicted according to its relationship to bus voltage. The 95% of the cases with voltage of 588 [V] had at least 320 [kW] available power capacity. As this capacity had to include both the traction and charging power, which at that time was 134 [kW], it left only about 185 [kW] for charging the on-board battery. The power cap based on position was the next step of the decision process. As the sum of traction and charging is now lower than the cap of 416 [kW], the bus could charge 185 [kW]. Overall, it resulted in total power demand on substation of 1053 [kW].

The decision that let the power demand go that high and also violate the current limitation was the power cap based on the IMC trolleybus position on the section. It failed to curtail the power demand neither in terms of the current nor in terms of the transmission losses, because the total bus power demand was below 800 [kW]. The power cap should have prevented the bus from drawing that much power to minimize the losses up to 10% of the total demand. Needless to say that the power cap data was created for one bus connected to the section and could therefore allow higher powers.

When comparing the power demand profile of substation 1 from figure 4.44 with the one of Best Case scenario from figure 4.15, almost all the violations now happened at places that were close to breaking the limit even with the communication employed. Figure 4.46 provides a comparison of the total power demand on substation 1 of the Best Case scenario and the first version of estimator. There is one time step marked on both data sets, for which the traffic situation is depicted in figure 4.45. At that time, trolleybuses were on both sections that are supplied by substation 1. While under Best Case scenario, the IMC trolleybuses did not charge, the estimator advised them to. According to the model logic, section 3 was simulated as a first one (IMC trolleybus on section 3 has the lowest number, 40, of all IMC). As the estimator evaluated the IMC vehicle not to be alone on section 3, the relationship between the bus voltage and the available power capacity suggested there should be enough capacity left to withstand its traction power demand of 149 [kW] and charging power of 231 [kW] on top of that. When IMC trolleybus on section 2 was simulated, the estimator allowed charging almost maximal power as it sensed it being the only vehicle on the section. At the end, each section contributed by 566 [kW] and 558 [kW] (sections 3 and 2, respectively) to the total power demand. If the section would be supplied from two separate substations, the job of the estimator would be considered on point. Neither current nor the voltage were broken as can be seen from table 4.7.

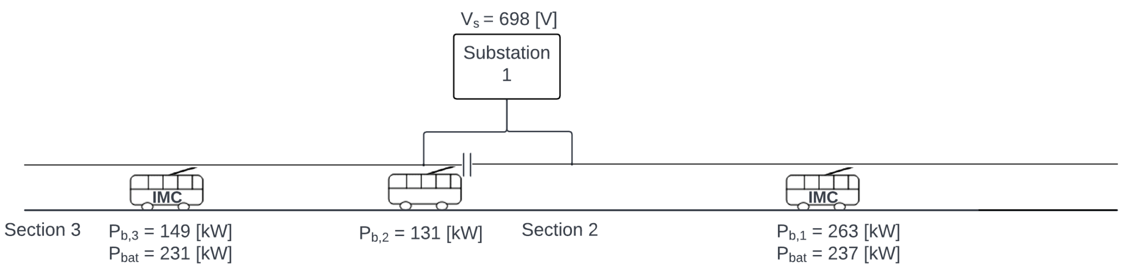


Figure 4.45: Situation on section 2 at t=15496 (approx. 9:15) on **day 1**. Section 3 is occupied by 2 vehicles, out of which 1 is IMC. Section 2 has 1 IMC trolleybus connected. Sections share substation 1. Estimator V1 Scenario

This example discovered a problematic circumstance on two sections powered by the same substation, when each section has at least one IMC trolleybus. The estimator relies heavily on the on-board measurements of voltage and current. As both of these parameters can only be altered by another vehicles' presence on the same section, they cannot reveal any information on what is happening on the section sharing the same substation. The Best Case scenario benefited from the communication

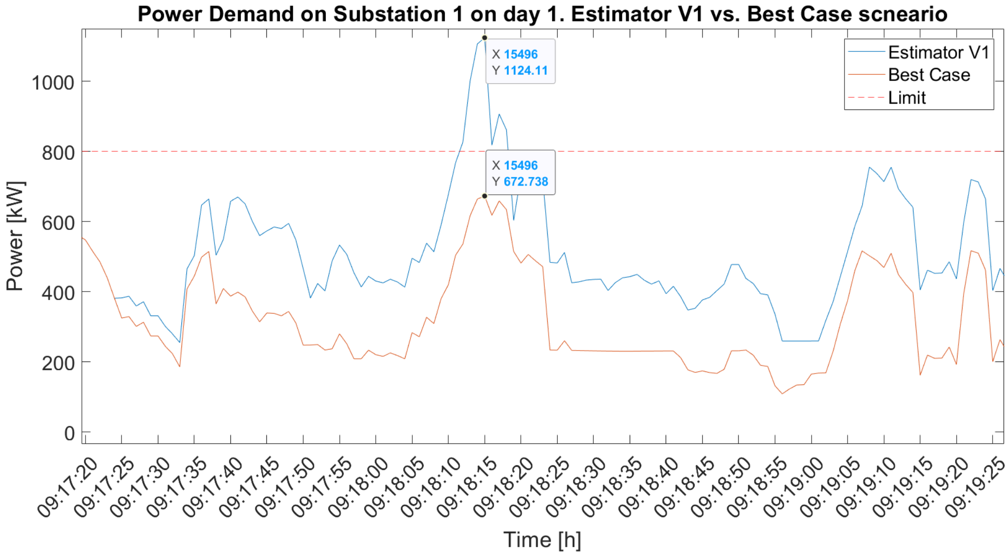


Figure 4.46: Power Demand on substation 1 on **day 1**. First version of estimator vs. Best Case scenario

Table 4.7: Voltage and current of each bus from t=15496 on **day 1**. Bus 1 is connected to section 2, buses 2 and 3 to section 3

Parameter	Bus 1	Bus 2	Bus 3
Voltage [V]	613	664	618
Current [A]	815	629	197

and had an insight even to the other section and thus decided to postpone the charging of on-board batteries. This is a major bottleneck of the estimator and the next versions of the estimators have to be more conservative to take to some extent these conditions into account.

Following three figures, 4.47, 4.48 and 4.49, show the maximal current and minimal voltage on each section and SoC of all IMC trolleybuses, respectively. Mostly when the current is over 840 [A], it is linked with too much of power demand. It is especially visible on sections 23 and 24 which are fed by substation 12. The power demand is slightly violated during the peak hours, in the morning and in the late afternoon. These are the periods where the largest peaks of current in the overhead lines are for sections 23 and 24. It is also interesting to notice that in between of these time periods the current violations are less severe. At that time, the power demand on substation 12 is well within the limit. This clearly claims that the technical parameters of the overhead lines also prevent the trolley-grid from being maximally utilized.

Except for section 2, the voltage on the sections seems to be coping with the extra load just fine. That does not apply to the SoC. The IMC trolleybuses were not able to pick up enough energy to make it through the whole day of operation and eventually depleted their battery very fast. Even during the first round trip, the SoC did not rise to the maximal 90% level and dropped below the recommended 20% threshold right after that. Although occasional adjustment of the allowed DoD would be acceptable in case of emergency (figure A.20 in app. A), the trolleybuses could not recover from it. Unlike during the Best Case scenario, section 38 (A station) is left out from the charging system. Mainly it is because with the estimator not having perfect information, the high traffic on section 38, which can reach up to 16 vehicles at a time, would make it complicated to estimate the charging power. However, from these results it can be said that the charging on section 38 might be necessary to secure full-day operation.

This scenario served to pinpoint spots where the first version of estimator failed, analyze why it happened and how its performance could be improved. The search was successful after analyzing day 1. Due to the fact that all the 5 other days would experience the same problems, results of these days are summarized in appendix A.

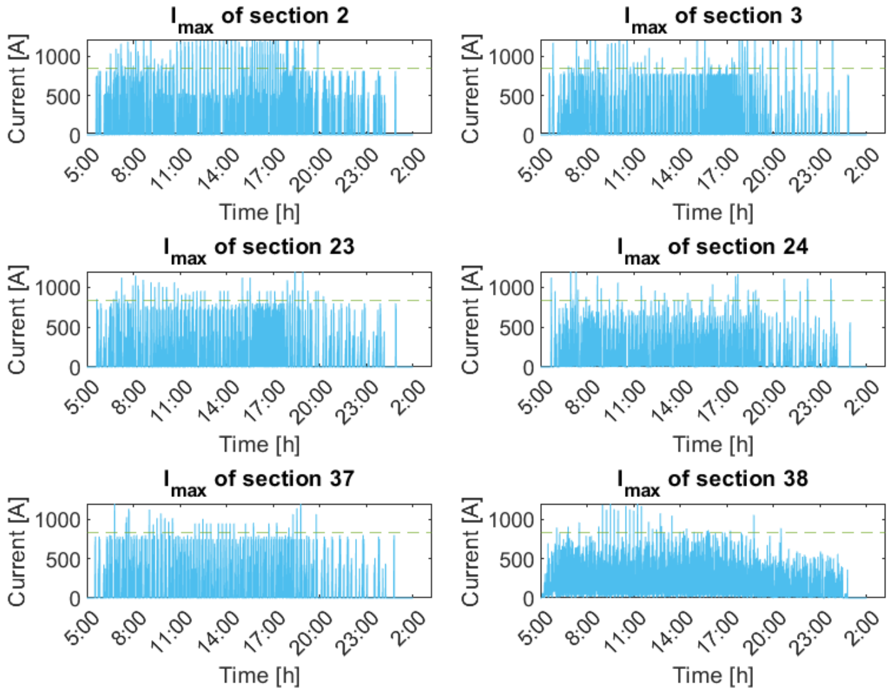


Figure 4.47: Maximal current on each section of line 352 route during **day 1**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V1 scenario.

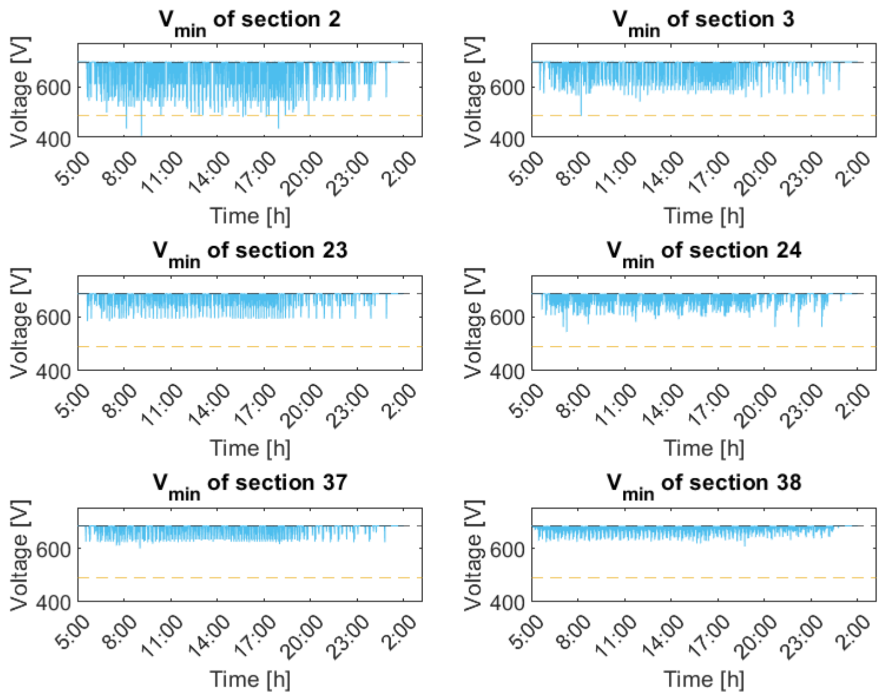


Figure 4.48: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

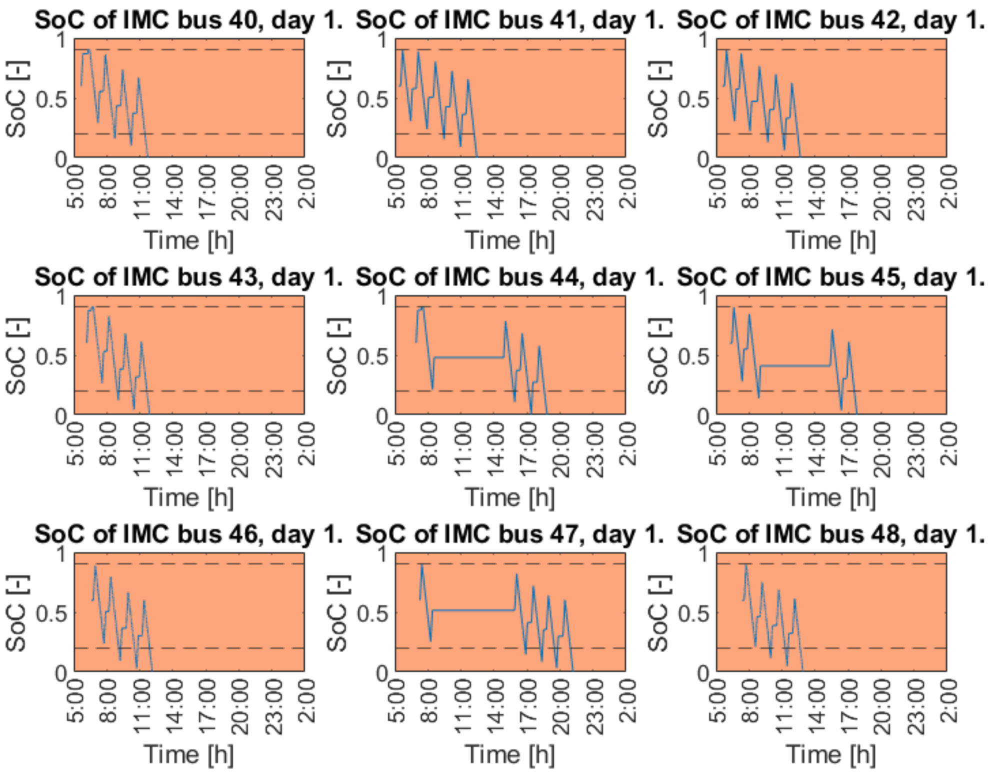


Figure 4.49: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 1**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

Energy collected

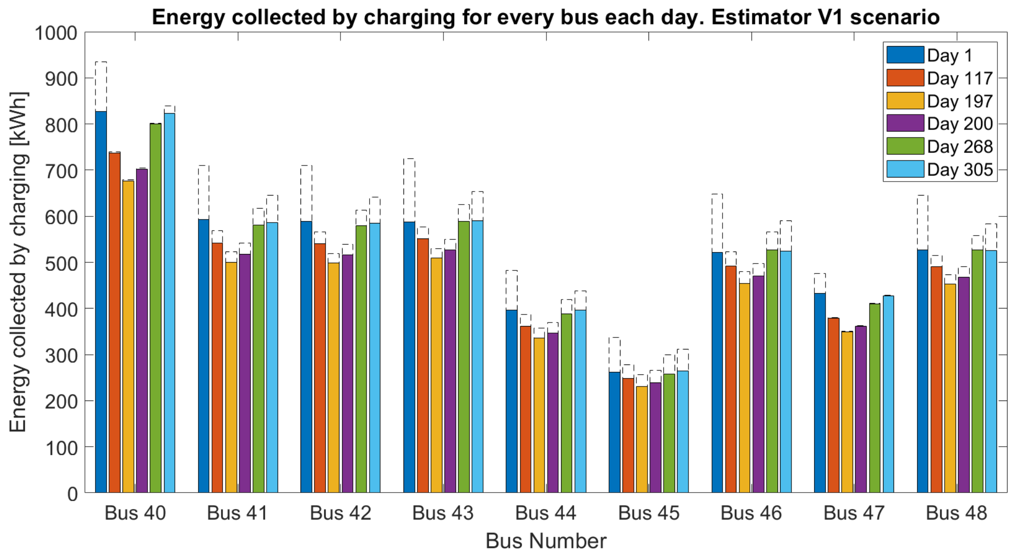


Figure 4.50: Energy collected by every bus each representative day of the year. Dashed transparent bars represent the potential energy to be collected. Estimator V1 scenario.

As already mentioned, the SoC of all IMC trolleybuses was not kept within the operational limits throughout the whole service day. The reason for that is that the total amount of energy collected was not sufficiently large. The dashed transparent bars in figure 4.50 represent the potential energy to be collected from Best Case scenario from figure 4.42. That is especially true for the demanding days 1, 268 and 305. There the energy stored in the battery decreased by around 150 [kWh], which is equivalent to almost twice the energy that could be charged within the operational region of the SoC of the battery (90% - 20%). The days where the traffic and energy consumption are lower did not experience that significant decline and the energy collected is similar. As the days are less frequently operated, there is probably also less obstacles that would prevent the IMC trolleybuses from charging.

4.4.2. Estimator V2 - Voltage, Current, Position Constraints for Multiple Vehicles

First version of estimator demonstrated that the trolley-grid requirements could not be met while multiple vehicles were connected to the same section. The constraints of the estimator were not able to ensure the suggested charging power did not cause especially current and substation power demand limitation to be violated. For the second version of estimator captured in figure 4.51, an improvement was made in the branch of $N > 1$. The last decision step used to compare the power capacity figured out by the relationship of bus voltage and the power capacity with power cap values for single vehicle on a section. This was proved too inaccurate for multiple vehicles and was replaced by power cap values for multiple vehicles $P_{\text{cap,multi}}$. The methodology and process of creating this data set is thoroughly described in section 3.5. The second version of the estimator will now allow the IMC trolleybuses to charge less power. It should be particularly beneficial in reducing the amount of cases which experienced substation power demand violations and current of more than 840 [A] in the overhead lines.

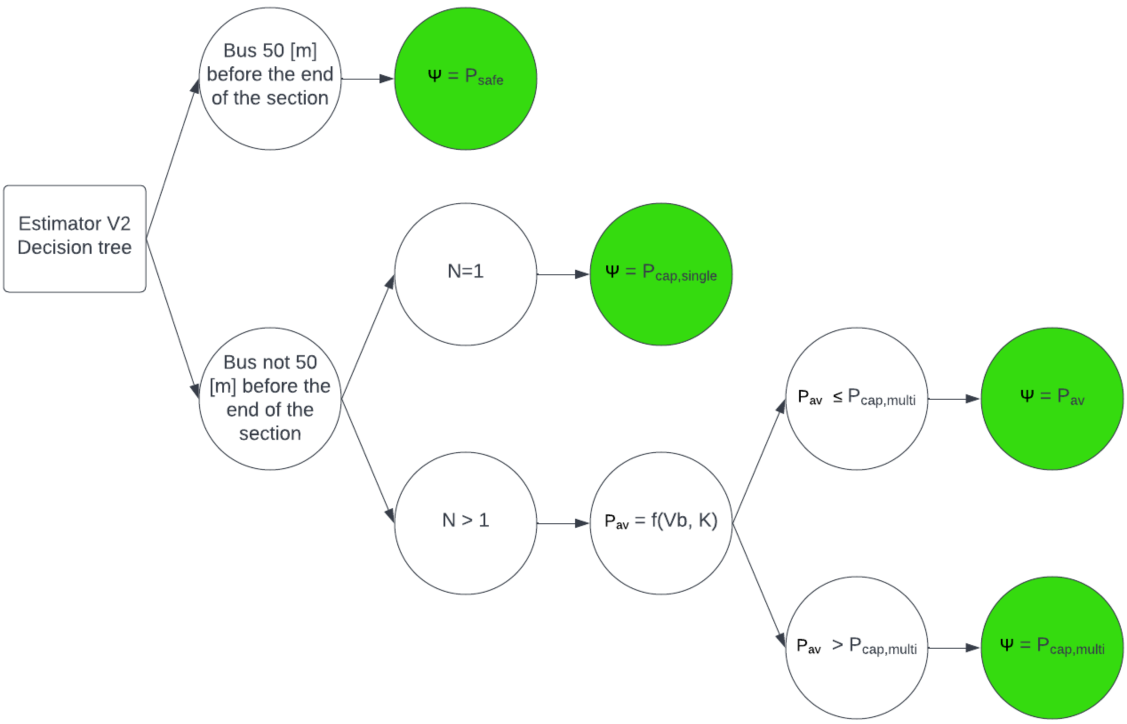


Figure 4.51: Decision tree of the second version of the estimator. Extended by position constraints for multiple vehicles on one section. Green circles represent final decision in the tree

Table 4.8 indicates how effective the improvement of power cap was. The total amount of violations was approximately halved in comparison to the first version of estimator. Voltage lower than 490 [V] almost disappeared. The few remaining they belong to moments where the situation on the section is so severe that it would lead to collapsing the trolley-grid. Even though it can be considered a big step forward, the number of persisting power and current violations is still high and further measures will

Table 4.8: Number of power, voltage and current limits violations per representative day. Second version of estimator based on voltage and current measurements and power cap for multiple vehicles on the section

Parameter	Day 1	Day 117	Day 197	Day 200	Day 268	Day 305
Power	550	601	512	472	594	549
Voltage	0	3	4	0	0	0
Current	1565	1061	1000	1037	1303	1400

have to be adopted to put it down.

Day 1

Using the more strict and conservative power caps for multiple vehicle made it possible to achieve the desired outcome of the situation presented in the previous section at $t = 11358$. The first version of the estimator could not detect the unsuitable moment for charging the IMC battery and its action would be harmful for the trolley-grid. Second version of estimator was more successful and thanks to the power cap for multiple vehicles the same result as in the best case scenario was reached. That cannot be said about the second example from previous section, at $t = 15496$, where the combination of traffic on sections 2 and 3 caused problems. The power cap values are only relevant for traffic on one section. Although one of the IMC vehicles shared section 3 at that time, the power cap value for multiple vehicles did not differ from the one for single vehicle.

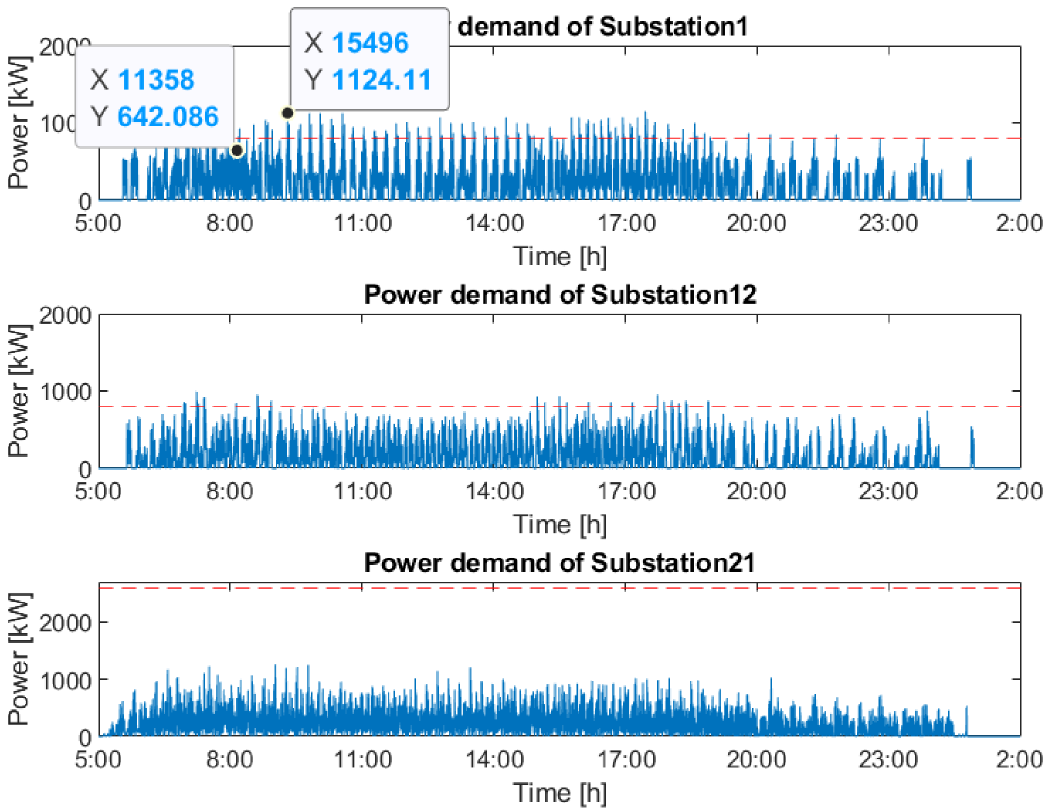


Figure 4.52: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 Scenario

With regards to voltage and current, the amount of violations was reduced even though it is not visible on first sight from figures 4.53 and 4.55. The peaks overshooting the 840 [A] could still be present in the curves but what could actually change is the duration of the peaks. A comparison of the duration of the peaks from first (blue bars) and second version (orange bars) of estimator is in figure 4.54. It can be seen that one-second peaks have almost not changed. On the other hand, the very long peaks of over 5 [s] have almost vanished as there is evidently less orange bars in that region. The peaks in orange have significantly increased at 3 [s] and 4 [s] which just proves the shortening of the duration. This is also very important factor to follow as the current limitation is a thermal safety limitation for the overhead lines. As the over-heating happens over time, reduction of the undesired circumstance is crucial.

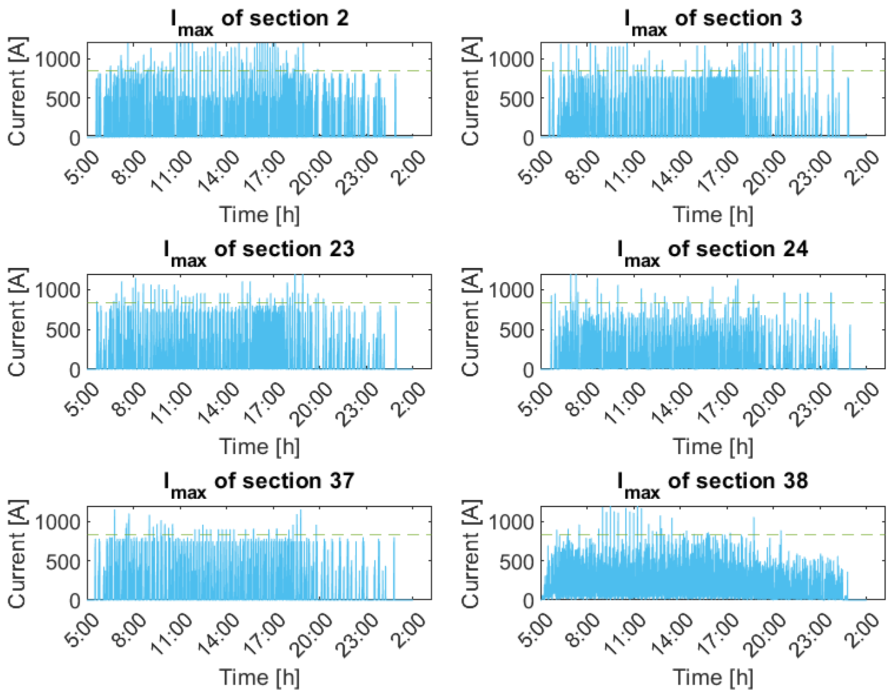


Figure 4.53: Maximal current on each section of line 352 route during **day 1**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V2 scenario.

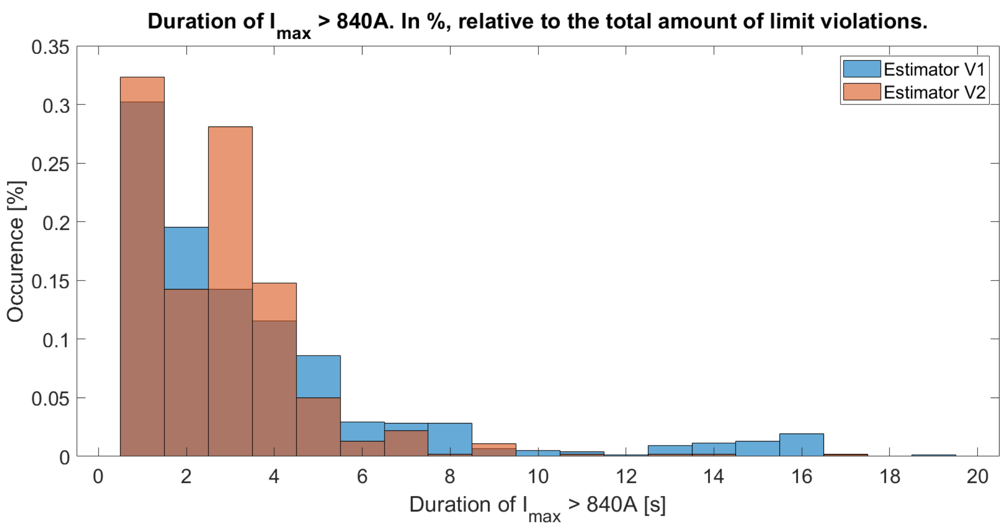


Figure 4.54: Duration of $I_{max} > 840[A]$. Histogram in percentage [%] relative to the total amount of current violations. Comparison of estimator V1 scenario (blue bars) and estimator V2 scenario (orange bars).

What requires special attention is the curve of SoC in figure 4.56. Even with the previous version of estimator the condition of SoC was not favourable, but as more measures to cut down the number of limit breaks has been adopted, the charging power reduced. This makes the line 352 inoperable on these demanding days and future versions of the estimator will not only have to focus on the violations but also on appropriately increasing the picked-up energy.

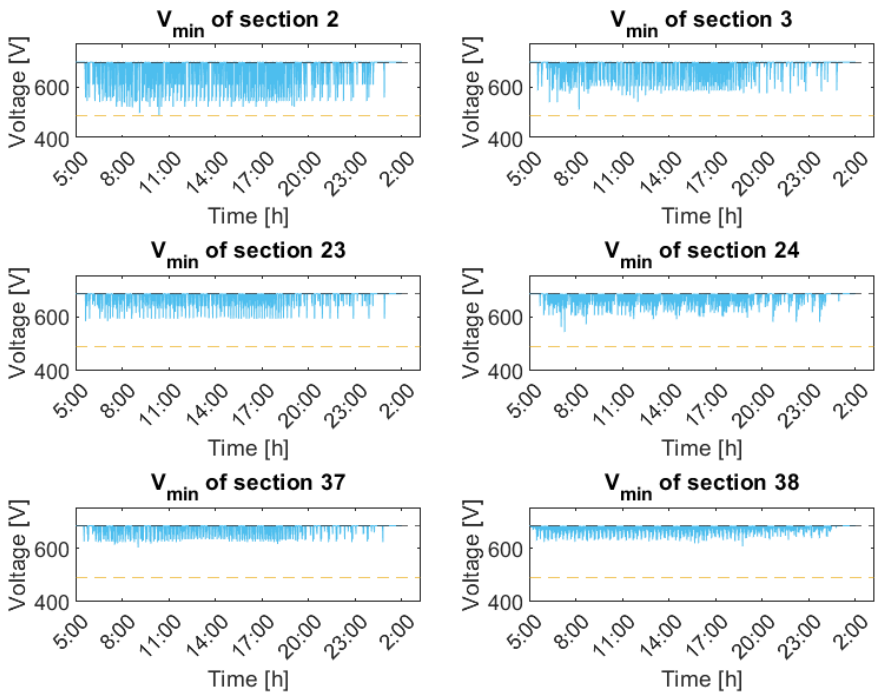


Figure 4.55: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

The rest of the days are presented without comments in appendix B. They show the same patterns as day 1. The SoC plot for day 268 in figure B.16 is worth mentioning, as even though it drops below the 20% threshold, it bounces back without complete depletion. However, with further reduction of the charging power, even this day will become inoperable.

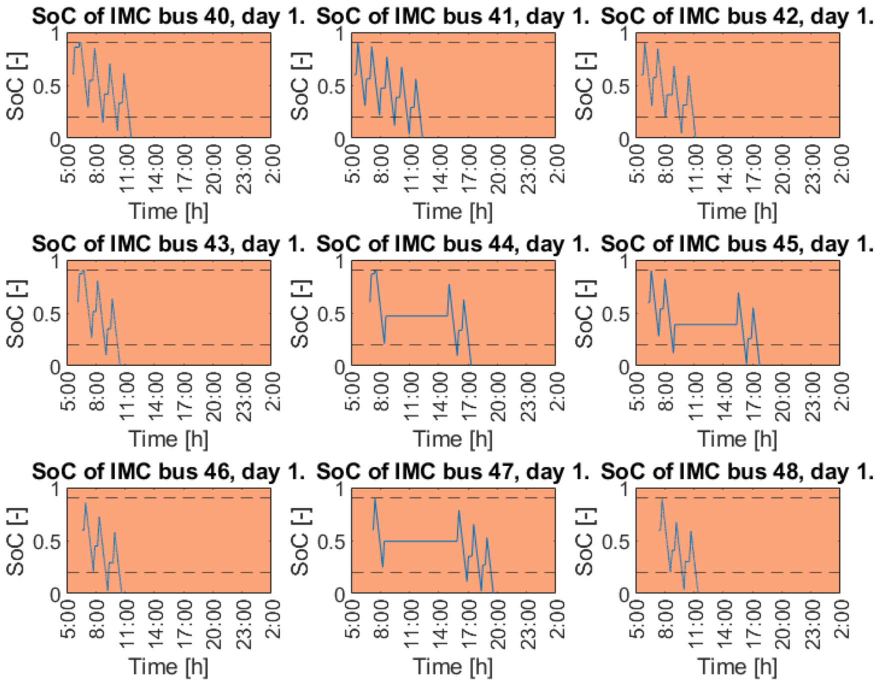


Figure 4.56: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 1**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

Success Rate of Estimator V2

In order to proceed further with improving the following versions of the estimator, an analysis of how successful the predictions of the estimator are was carried out. The first factor to inspect was how accurate is the prediction of the number of vehicles connected to the same section based on the calculation of I_σ and the measurement of bus current I_b. It was only checking the traffic when the condition was being actually evaluated in the estimator, meaning only with maximal frequency of 3 [s] for each bus. Also, the data are cumulative for every day and every IMC trolleybus simulated. There are two subplots in figure 4.57, one on the left for cases when condition was evaluated as correct (only vehicle on the section) and one on the right for cases evaluated as wrong (multiple vehicles connected on the section). It can be seen that some cases where there are at least two vehicles on one section still claimed there is only one vehicle. This can have various reasons. Firstly, the difference between I_σ and I_b can be fluctuating around 0,5 used in the condition and this minor error causes the incorrect evaluation. On top of that, there can be cases when there actually are multiple vehicles but some of them might be braking, sending their recuperated energy to other trolleybuses and therefore affecting the current in the overhead lines. The phenomena of measurement blinding due to the trolleybuses connected on the opposite sides from the feeder cable (section 3.6) could also play its role. All these reasons can be supported by the fact that there are no cases when the condition is evaluated as wrong but there is actually one trolleybus only.

Next aspect to study is the accuracy of the function determining the available power capacity based on voltage $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$. This decision maker only takes part when there are supposed to be multiple vehicles on one section. For the purpose of this study, a difference of the P_{av} suggested by the estimator and the actual available power capacity that the substation could actually provide, P_{capacity}, was made. The latter values were created by adding together the bus power of all non-IMC vehicles fed by the same substation and then deducting 10% to account for transmission losses. The histogram of results can be seen in figure 4.58. Same rules apply to this plot as to the previous one, data are cumulative for all IMC trolleybuses and for all simulated days. There was quite a mismatch between the two quantities

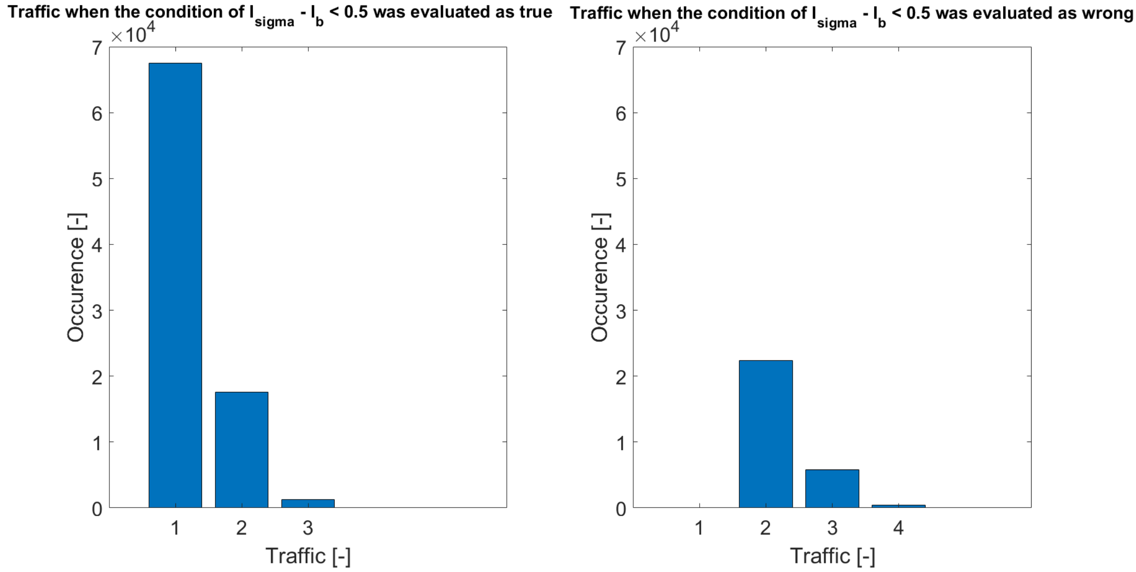


Figure 4.57: Traffic based on $I_\sigma - I_b < 0,5$ evaluation. If correct, there should be exactly 1 trolleybus on the section. If wrong, there should be multiple vehicles. Cumulative data for all IMC trolleybuses and all simulated days. Estimator V2 Scenario

ranging all over the possible range of 0 - 720 [kW]. The difference from 140 [kW] to 420 [kW] accounts for approx. 80% of all the cases from almost 30 000 times when this branch of the decision tree was stepped in. The insufficient amount of energy collected has roots in here. To provide justification for using this function, it has been, or more precisely the confidence level, made very conservative to minimize the number of violations caused. That is why the function keeps suggesting low available power capacities even though there might be more to take from the substation.

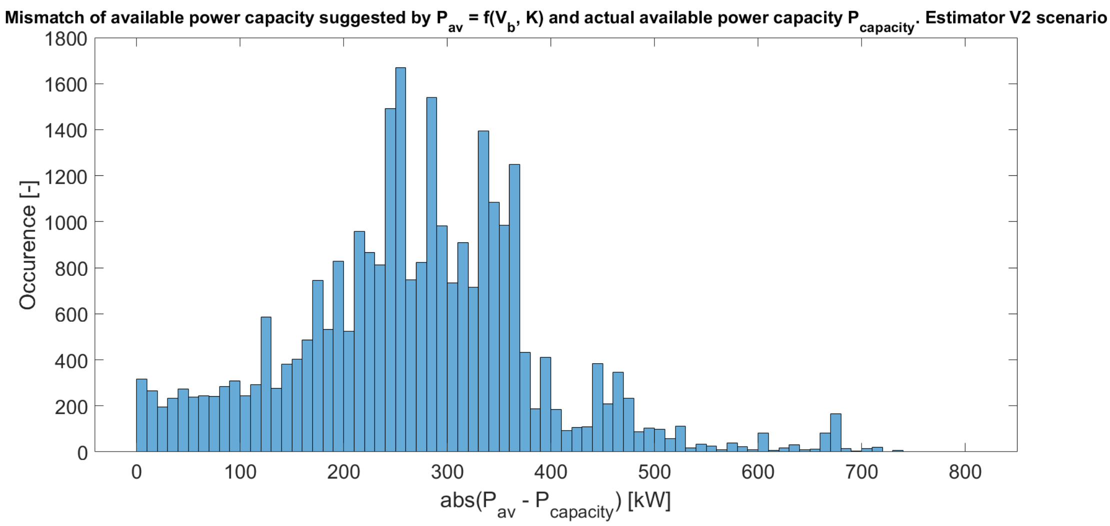


Figure 4.58: Mismatch of available power capacity suggested by $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$ and actual available power capacity P_{capacity}. Cumulative data for all IMC trolleybuses and all simulated days. Estimator V2 scenario

As could be seen from the results presented so far, the most problematic parameter was the current in the overhead lines. In order to react to it, the traffic density was analysed when the limitation of current was broken. From plot in figure 4.59, the traffic as well as the magnitude of the maximal current can be studied. There are no violations when there is only one vehicle on the section, thanks to power cap for single vehicle values. A positive finding is that the number of violations for 2 vehicles is minimal, which means that the trolley-grid in Arnhem can definitely take at least two vehicles while at least one of them is IMC trolleybus. Also, the magnitude of current is very close to the limit of 840 [A] for these cases. It starts to get problematic with 3 - 5 vehicles. Cases of 5 vehicles also show the highest currents. With regards to traffic of 5 and more, these conditions could only happen on section 38 (A station), through which all the trolleybuses in Arnhem public transport network pass.

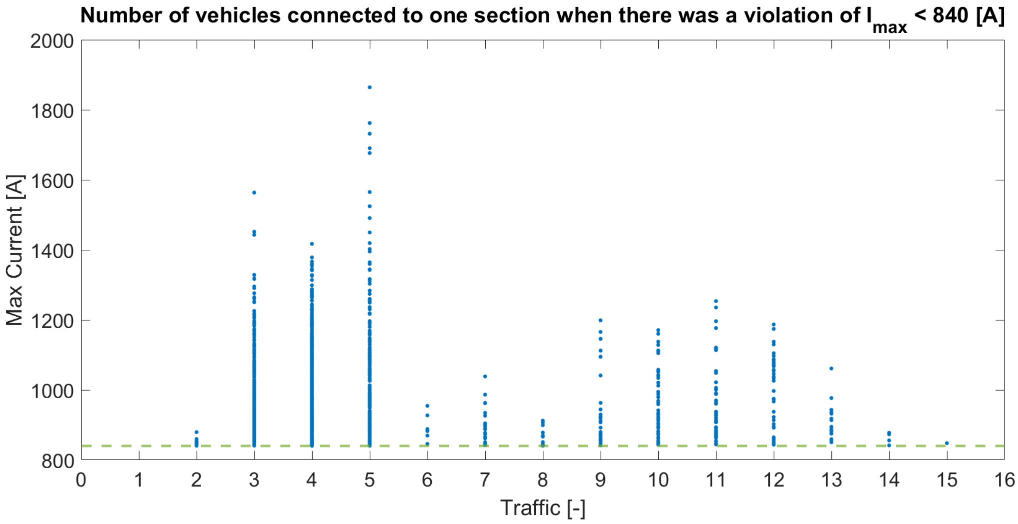


Figure 4.59: Traffic when the limit of 840 [A] was violated. Y-axis shows the magnitude of current in the overhead lines. Green dashed line represents the limit of 840 [A]. Cumulative data for all IMC trolleybuses and all simulated days. Estimator V2 scenario

As the previous plot may be misleading in terms of how many times it happened, next figure (4.60) provides a histogram of the traffic. It proves 3 vehicles to be the cause of most of the current violations. They might make the measurements and predictions ambiguous as for example just 3 vehicles accelerating can already demand up to 900 [kW]. On the other hand, there is little possibility of all of them braking for example. With 4 vehicles, the probability is decreasing and at least one of the vehicles affect the measurements in such way that the estimator evaluates them correctly and suggests low charging powers. Also, except for 2 vehicles on the same section, 3 vehicles are the most frequent. Generally, it can be claimed that the current is overshot in cases of more than 3 vehicles on one section. Future improvements made in the estimator should focus on reducing the demand while multiple vehicles connected. It also makes it clear that the amount of violations on section 38 (traffic > 5) is not so serious and that this section could potentially be in some way included in the charging scheme.

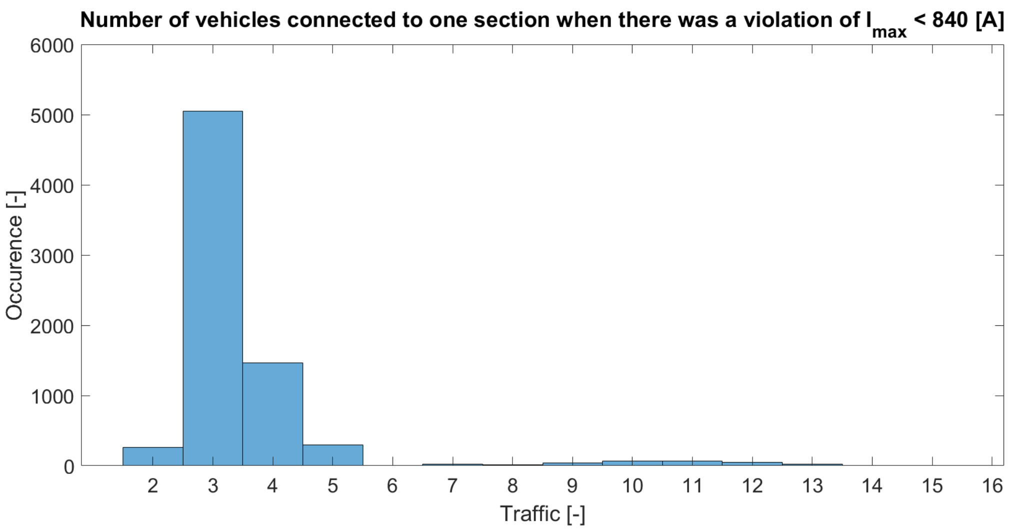


Figure 4.60: Histogram of traffic when the limit of 840 [A] was violated. Cumulative data for all IMC trolleybuses and all simulated days. Estimator V2 scenario

Energy Collected

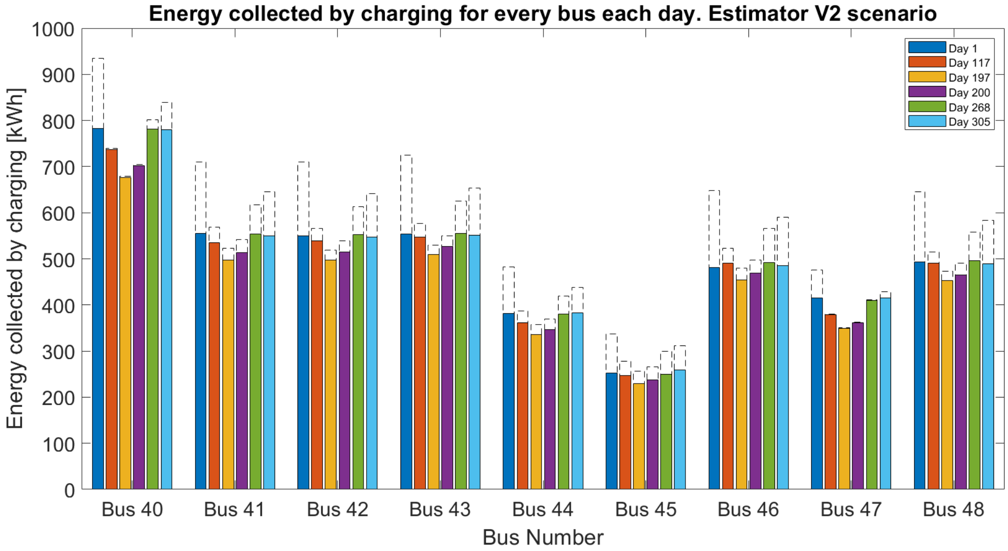


Figure 4.61: Energy collected by every bus each representative day of the year. Dashed transparent bars represent the potential energy to be collected. Estimator V2 scenario.

The amount of energy collected has generally decreased. The reason for that has already been explained. The percentage of decrease is similar for all the days simulated. With implementing more constraints to ensure the safety limits of the trolley-grid are met, the decline could be even deeper.

4.4.3. Estimator V3 - Voltage, Current, Position Constraints for Multiple Vehicles, Charging Priority

After elaborating on the previous results, vast majority of the safety limit violations still happen while multiple vehicles are on the same section (or fed by the same substation). To further support the implementation of the power cap for multiple vehicles, another approach taken is working with a charging priority. The charging priority can be visualized as certain level of certainty/confidence the IMC trolleybus has at certain point on its route to charge. So far, the former versions of estimator worked with confidence for predicting the available power capacity on section based on the bus voltage. This has been set firmly to 95% requiring at least 95% probability that the substation can provide this power. Contrarily, the charging priority distinguishes low priority and high priority. The former applies to all the IMC vehicles that have entered Arnhem trolley-grid in Oosterbeek and continue towards A station. Generally, the direction is from off-grid to on-grid. These trolleybuses still have a lot of time under the overhead lines where they can charge the battery ahead. By purposely curtailing their charging power in this direction, they create space for IMC trolleybuses going the other, high priority, direction, from A station to W (on-grid to off-grid). They are about to leave the trolley-grid soon and thus should maximize their collected energy to safely make it in the autonomous mode.

Having described the charging priority, the previous decision tree for estimator V2 was changed. The branch for trolleybuses close to the section switch remained the same, but the part of the tree for all the other cases was divided into two parts, one for each direction/charging priority. For both directions, when the estimator evaluates the number of vehicles on the section to be equal to 1, the final charging power is determined based on the power cap values based on position of the single vehicle on the section. In this case, there is no point of taking the charging priority into consideration. When there are supposed to be more vehicles connected, direction from W to A remains the same. The other direction makes the IMC trolleybus charge $P_{safe} = 50[kW]$. This measure reduces the stress put on the substation and the overhead lines and it should further help to make the use of Valley-Charging approach for IMC vehicles violation-less.

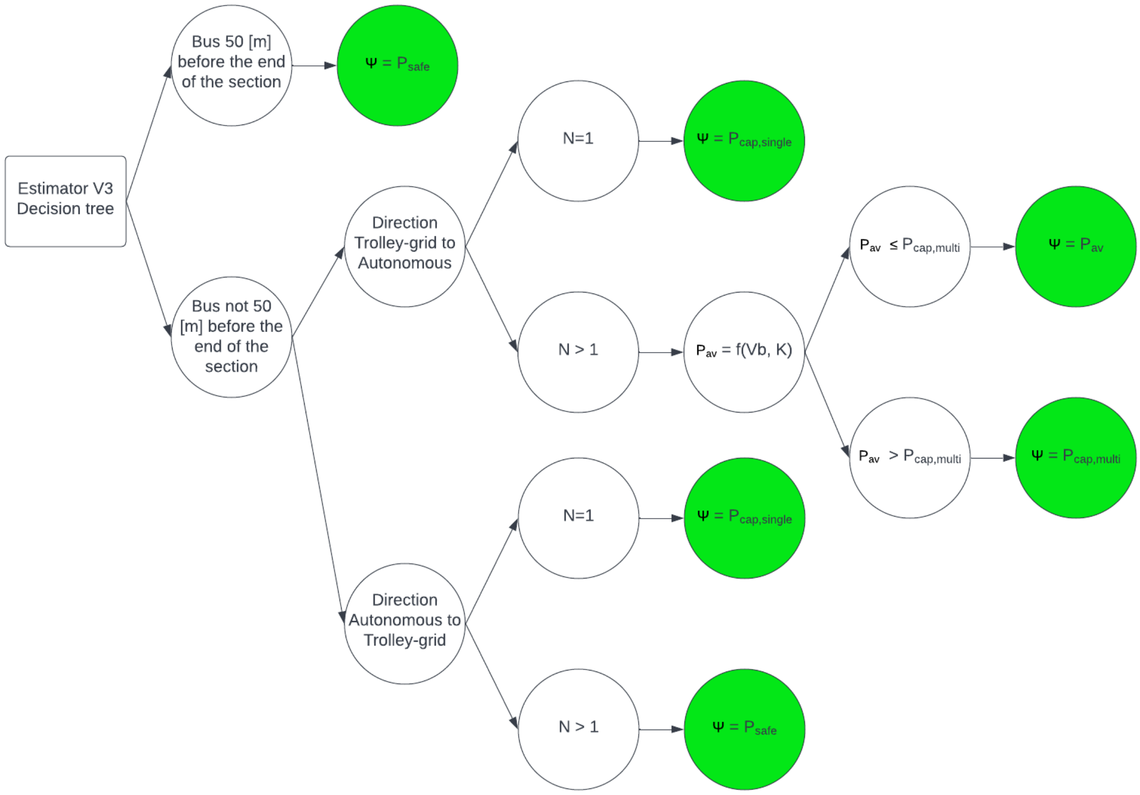


Figure 4.62: Decision tree of the third version of the estimator. Extended by charging priority based on the direction of line 352. Green circles represent final decision in the tree

Table 4.9: Number of power, voltage and current limits violations per representative day. Third version of estimator based on voltage and current measurements, power cap for multiple vehicles on the section and charging priority based on direction

Parameter	Day 1	Day 117	Day 197	Day 200	Day 268	Day 305
Power	452	441	363	365	385	449
Voltage	0	3	4	0	0	0
Current	851	448	471	501	634	895

The employment of charging priority brought again massive improvement in terms of the number of violations. They halved compared to the previous version of estimator. If not only the amount but also the seriousness has changed, infrastructural changes might already be suggested to get rid of the undesired violations.

Day 1

When the power demands of all the substations from day 1 achieved with the third version of estimator (figure 4.63) are compared with the ones of second version of estimator from subsection 4.4.2, it can be seen right away that some of the peaks going above the allowed limit are gone and the power demand was adjusted appropriately. Time step $t = 21764$ (approx. 11:00) can be mentioned as an example, reducing the total power demand from 942 [kW] to 628 [kW]. Even though the charging priority worked accordingly and helped to prevent the trolley-grid from breaking the limits, it left almost 170 [kW] power capacity unused, which can be considered as a waste of charging potential. It can be claimed waste while there was the maximal current of only 714 [A] in the overhead lines, leaving almost 120 [A] unused. The charging priority solution works, but it is more of a robust one, not trying to optimize the charging power.

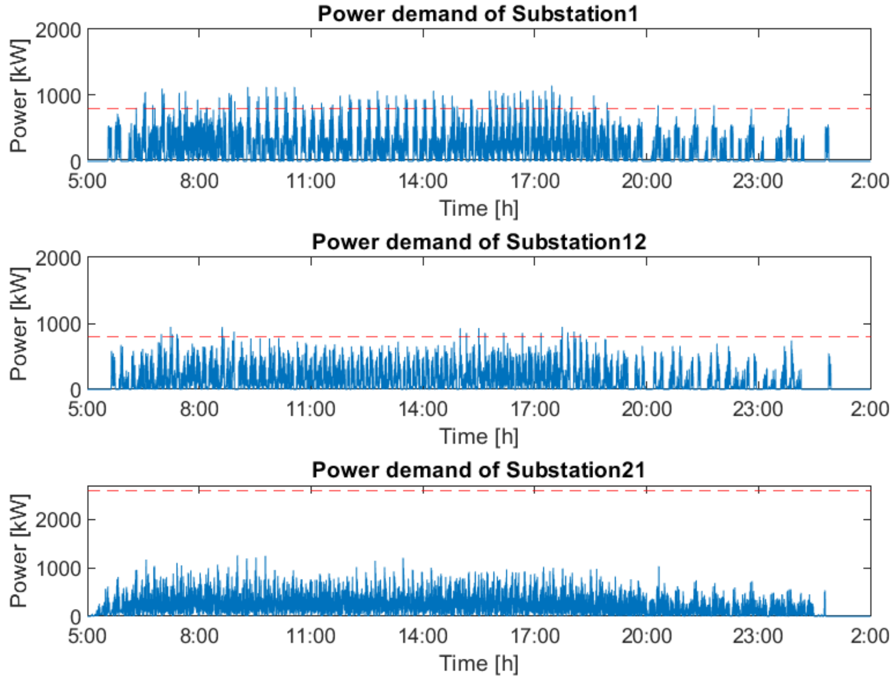


Figure 4.63: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 Scenario

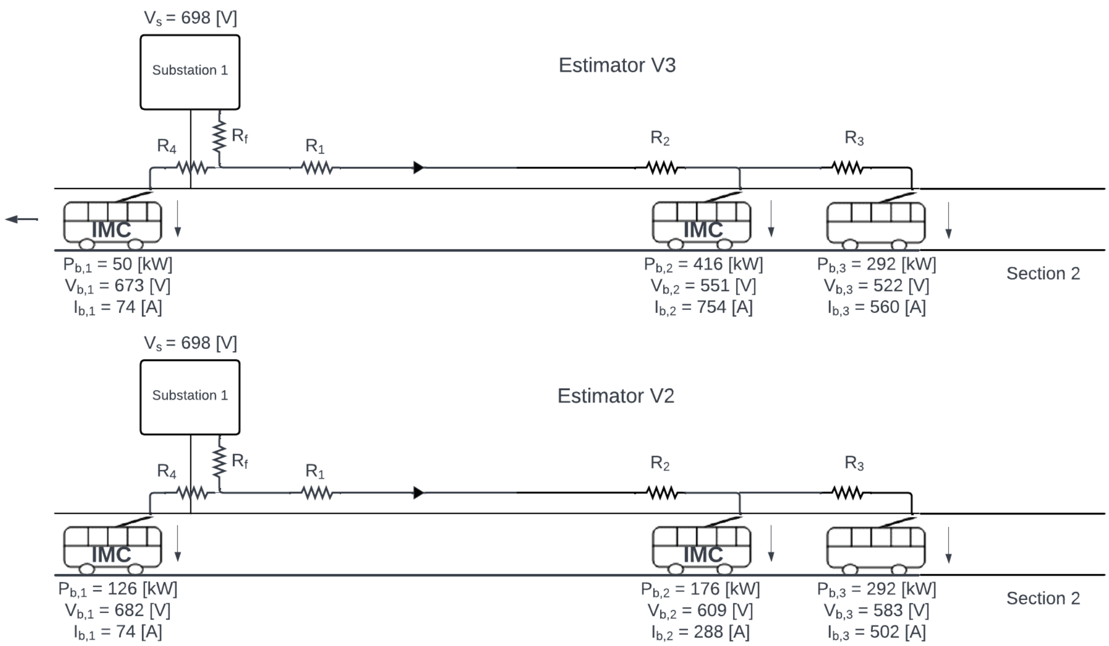


Figure 4.64: Situation on section 2 at t = 30839 (approx. 14:00). Two IMC vehicles and one regular trolleybus connected. Upper chart - estimator V2. Bottom chart - estimator V3

However, in the same figures there can be some cases spotted where the effect was the exact opposite. As the power demand of one vehicle dramatically reduced, it might have affected the values of current and voltage is such way that the estimator evaluated the measurements inappropriately for another IMC vehicle also connected to the same section. An example of this is captured in figure 4.64 where the traffic on section 2 is. This time step clearly is within the power demand limit demanding 590 [kW] and almost within the current limit, 863 [A]. By introducing the charging priority, they both increased to 937 [kW] and 1389 [A].

The decision making of the estimator happened 2 [s] before this time step in both cases. For estimator V2, it started with vehicle 1 from figure 4.64 which at that time was braking. The estimator correctly suggested there are more vehicles. Based on the relationship between bus voltage and available power capacity, 560 [kW] should have been ready to use. This high value is justified by the position of the vehicle 1 on the opposite side of the feeder cable than the other two vehicles. The position also allowed the vehicle to charge maximally, 240 [kW], for the next 3 [s]. As it already wanted to store its regenerated energy to the battery, just 126 [kW] could be taken from the grid at $t = 30839$. In terms of IMC trolleybus 2, it also sensed presence of other vehicles, suggesting 410 [kW] should be available based on its voltage. After deducting the bus traction power, it was left with around 210 [kW]. However, when it was checked with the power cap value for multiple vehicles, just the traction power demanded too much and charging power had to be made 0 [kW] for the following 3 [s]. It resulted in one IMC vehicle charging half of its potential and the other not charging at all.

For estimator V3 which already have the charging priority based on direction active, IMC trolleybus was spotted going towards A station. As it sensed there is more than one vehicle on section 2, it was advised to charge $P_{safe} = 50[kW]$. Interesting circumstances led the estimator evaluate IMC trolleybus 2 to be the only one on the section. The currents measured and calculated were as follows:

$I_b[A]$	$I_\sigma[A]$
365,8	365,4

When compared to these values for estimator V2, the difference was larger:

$I_b[A]$	$I_\sigma[A]$
367,8	365,4

The current I_σ is being calculated with values from time step (t-1). At (t-1), the power demand of regular trolleybus 3 was just -3,3 [kW] denoting braking. This trolleybus could barely affect the amount of current in the overhead lines. The reason for these inconsistent evaluation results is then IMC trolleybus 1. For estimator V2, it required enough power from the substation to cause voltage drop at the feeder cable large enough to force the current going to IMC trolleybus 2 to be higher and the estimator could predict presence of bus 1. In the case of estimator V3, 50 [kW] were not enough and estimator decided IMC trolleybus 2 to charge maximal charging power.

This malfunction of the estimator resulted in one of the highest peaks of current on section visible in figure 4.65. It can also be seen how less dense the blue curve is above the 840 [A] limit thanks to the integration of charging priority. Voltage remained exactly the same as with the previous version of estimator. What is still getting worse is the SoC (figure 4.67). The charging priority measure is definitely not focused on increasing the charging power/energy collected and solely deals with too high power demand and related over-heating of overhead lines due to high traffic. It is for sure that the next version of estimator needs to prioritize SoC to make line 352 operable.

Another lesson learned from example in figure 4.64 is the fact that the estimator only updates each 3 [s]. IMC trolleybus 2 was advised to draw a lot of power because the circumstances were favourable at the time of measurement evaluation. What happened after two more seconds has already been presented. Reduction of the updating time could positively affect both the number of violations by being potentially more accurate and thus also the energy collected. The estimator would kick-in during the example scenario sooner and based on the voltage drop and the mismatch in currents I_σ and I_b would suggest lower charging power.

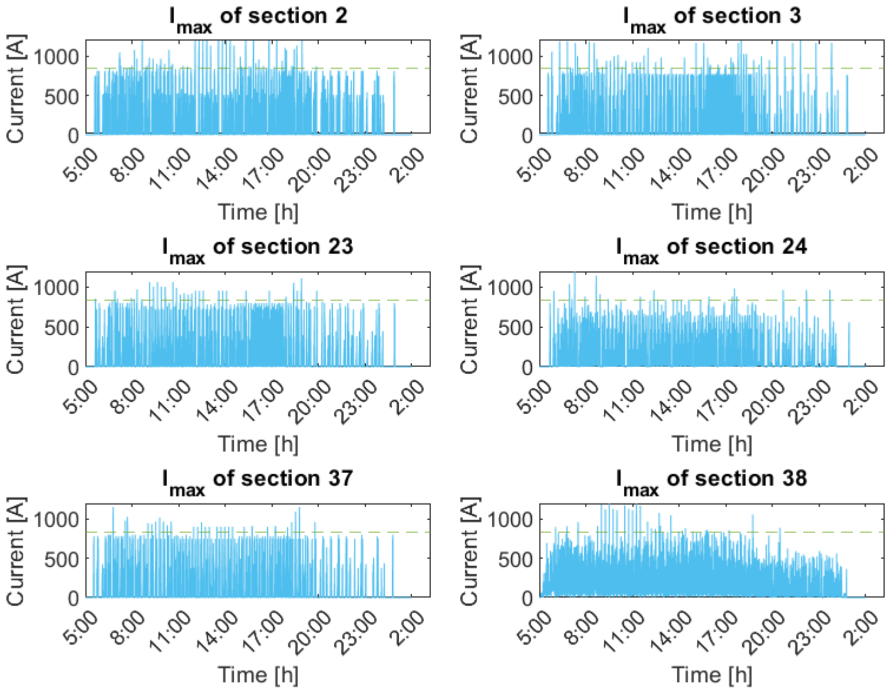


Figure 4.65: Maximal current on each section of line 352 route during **day 1**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V3 scenario.

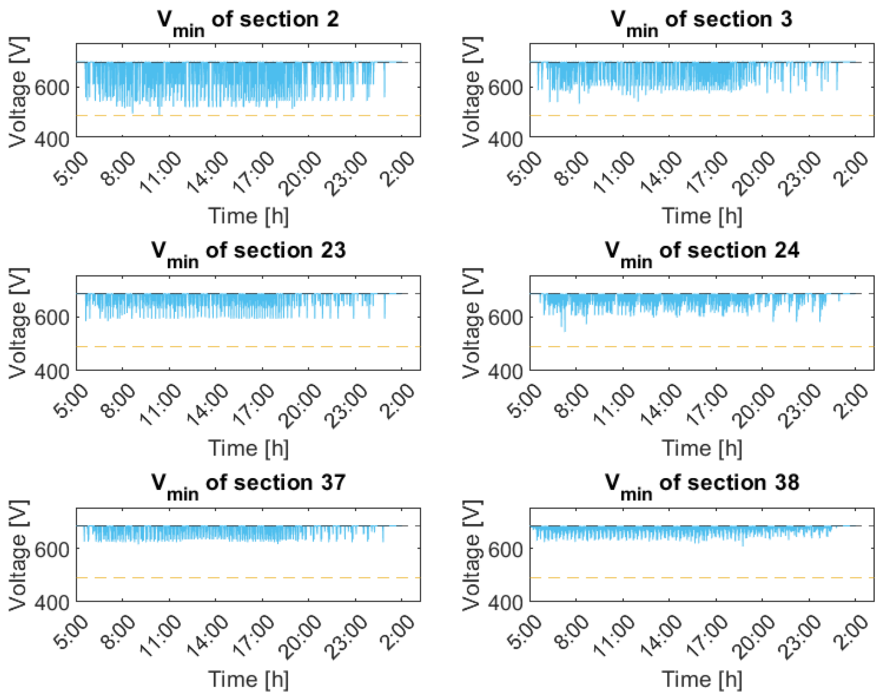


Figure 4.66: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

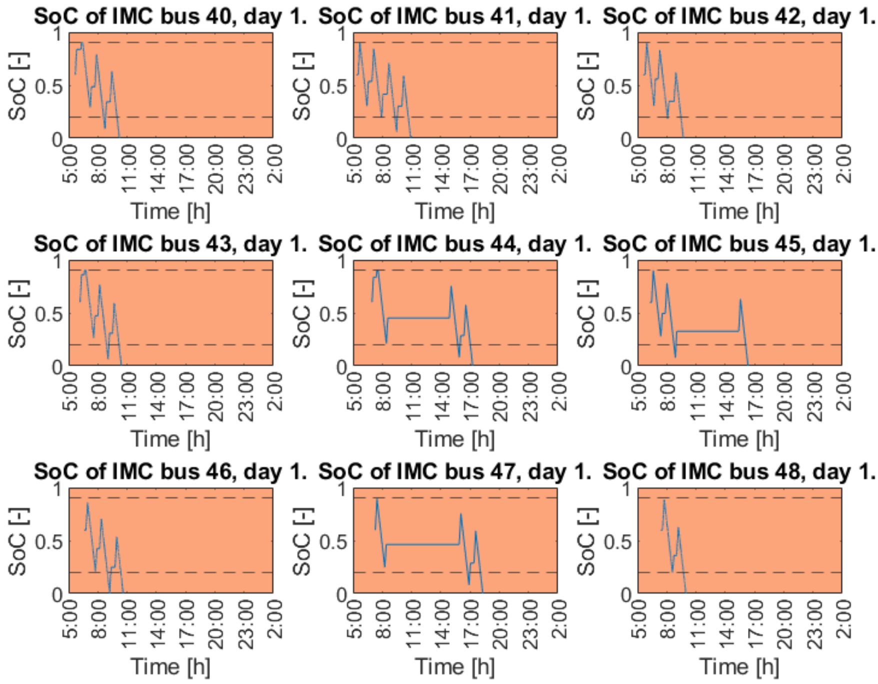


Figure 4.67: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 1**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

The rest of the days are presented without comments in appendix C.

Energy Collected

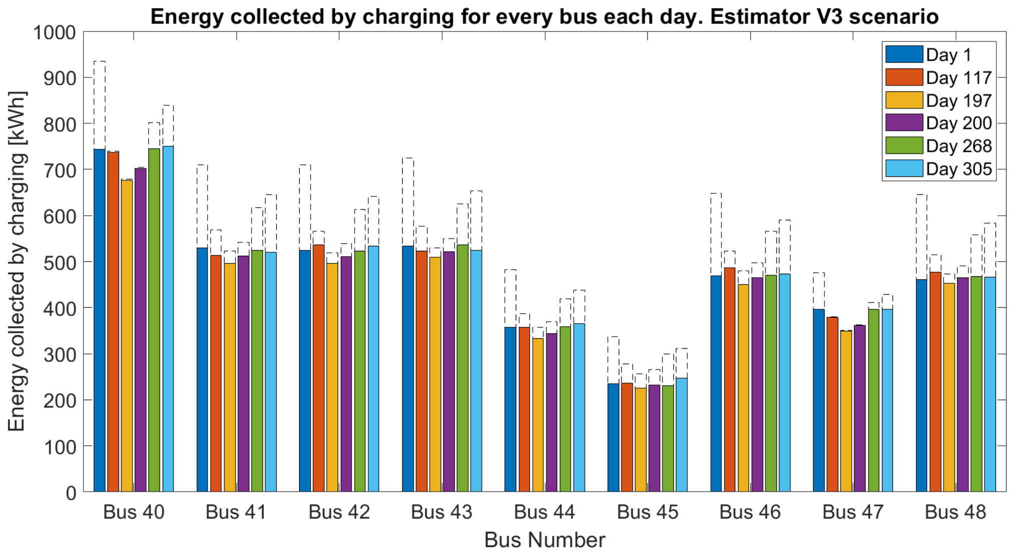


Figure 4.68: Energy collected by every bus each representative day of the year. Dashed transparent bars represent the potential energy to be collected. Estimator V3 scenario.

Together with applying grid-safety measures, the energy collected and stored in IMC on-board batteries is getting lower. The biggest difference from previous version of estimator is about 40 [kWh]. When compared to the Best Case scenario from section 4.3, especially bus 40 was able to pick-up about 200 [kWh] less on day 1.

Another interesting insight is that some days, namely day 197 and 200, do not show any alterations in the energy collected. For most of the buses, their values are exactly the same for the last two versions of estimator. So while the trolleybuses collect less during the other days, they are equally successful during the aforementioned days. The bars related to one trolleybus in figure 4.68 are getting more flat as the amount of energy stored in battery is more balanced.

The fourth and last version of the estimator is presented in the following chapter 5. Firstly, the shortcomings of the estimator version 3 are described. Then, the new mechanisms of the estimator are introduced.

5

Estimator-Supported Valley-Charging Approach - Arnhem Case Study

Chapter 5 aims at presenting the results of the simulation of Arnhem Case Study. The IMC trolleybuses use Valley-Charging scheme supported by the most complex version of the estimator in this thesis. Section 5.1 includes simulation results of line 352 of all the 6 representative days. This section also evaluates how were the estimation methods successful at predicting the state of the trolley-grid. Section 5.2 compares the Valley-Charging scheme with conventional schemes. Last section 5.3 aims to explain one of the benefits of the Valley-Charging scheme which is the ability to adapt to change of conditions at the trolley-grid.

5.1. Final Estimator Version

Previous version of the estimator focused exclusively on reducing the number of limit breaks. That came along with the reduction of the energy collected. The Best Case scenario used the benefit of section 38 (A station) and the waiting time there for charging. Based on the plots of SoC (for example figure 4.20) for that scenario, it is evident that charging on this section was crucial to keep the battery within the SoC limits. The same needs to be done now, charging on section 38 will be allowed. As the section is characterized by high traffic density (maximal amount of vehicles can go up to 16 vehicles) and by mostly idling trolleybuses, the estimator will not be used to evaluate the measurements of voltage and current. In exchange, the batteries will be charged with constant power $P_{\text{safe}} = 50[kW]$ based on their SoC. In this case, the estimator will not control the magnitude of charging power but the duration of charging. Even though the battery could be potentially charged much more on section 38, the journey under the overhead lines would be a waste of charging potential. Also, due to the traffic on section 38, it is desired to minimize the demand on the section. This measure is applicable to any high traffic public transport terminal where the vehicles typically spend lower minutes idling and can use that time to charge their on-board batteries. With conditional charging, the section is less prone to too high power demand from multiple vehicles at the same time.

Previous results also showed that not only the energy collected is not enough but also the battery size might be too little. To achieve operation without dropping to the bottom limit of 20% SoC, the capacity of the battery will be increased by 20 [kWh] to 130 [kWh].

In order not to waste the time under the overhead lines with full SoC, an estimation of what should be charged on section 38 will be made to charge the rest on the way to the exit from the trolley-grid to successfully overcome the autonomous part with the battery energy. Firstly, the SoC needed for the whole autonomous part of the journey needs to be determined. An energy consumption of 2.5 [kWh/km] (including traction, HVAC and regenerative braking) is the worst case scenario throughout the year. Taking into account the distance of the autonomous part mentioned in section 3.3, the value would be:

$$SoC_{\text{autonomous}} = \frac{E_{\text{cons,max}} \cdot 2d \cdot 1.2}{E_{\text{bat,max}}} \frac{2.5 \cdot 14.4 \cdot 2 \cdot 1.2}{130} = 66.5[\%] \quad (5.1)$$

This is the value of SoC that will be ”consumed” during the autonomous part of the route. The operational region of the battery needs to be taken into account as it is not desirable to deplete the battery fully, which adds another 20% not to reach the bottom limit. The final value of $SoC_{\text{autonomous}}$ is 86.5 [%]. It is the SoC that the on-board battery needs to have when leaving the trolley-grid to successfully make it back in the worst case.

Each IMC trolleybus can on average collect 29 [kWh] of energy per one-way trip under the overhead lines and store it in the battery. In terms of the SoC, it is:

$$SoC_{\text{gain}} = \frac{29}{130} = 22.3[\%] \quad (5.2)$$

The final condition for charging on the Centraal station relies on the difference between $SoC_{\text{autonomous}}$ and SoC_{gain}. If the SoC of the vehicle is lower than this difference, the bus should charge as it would not collect enough energy under the overhead lines. If it is higher, then it can stop.

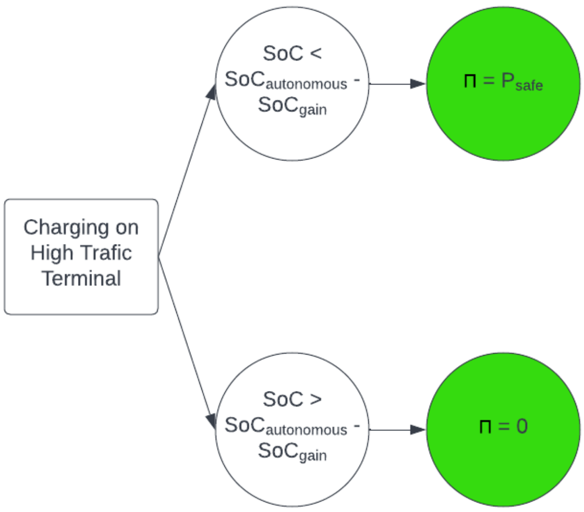


Figure 5.1: Process of charging on high traffic public transport terminal. In the case of Arnhem, section 38.

This gives the last part of the final version of the estimator. The process diagram that can be seen in figure 5.2 uses the same conditions and constraints as the previous one and on top of that utilizes the charging potential on section 38. Based on the table of failures 5.1, it can be claimed that including the last section into the charging scheme is definitely beneficial. As the substation 21 feeding section 38 is oversized in terms of the power capacity (limit of 2600 [kW] instead of 800 [kW]), there are no new power limit violations compared to estimator V3. With regards to the current limit, there are new violations on the rush days 1, 268, 305. As the traffic on section 38 can reach up to 16 vehicles at the same time, just assuming 45 [kW] of HVAC demand of each of the vehicles might cause a problem not even considering the newly added charging. Nevertheless, the increase in current limit violations is acceptable.

It is very important to realize that even with this advanced version of the estimator there are violations of the substation power and overhead line current limits. To have more accurate results, a better understanding of how the trolleybuses affect each other is necessary. As will be shown in subsection 5.1, the estimation methods sometimes misjudge the situation and suggest incorrect availability of power. Vast majority of the inaccuracies happen when multiple vehicles are connected to the same section. The estimator can only differ between number of vehicles $N = 1$ or $N > 1$. While for one

Figure 5.2: Decision tree of the fourth version of the estimator. Extended by conditional charging on high traffic public transport terminal. In case of Arnhem, it is section 38 Arnhem Centraal station. Green circles represent final decision in the tree

Table 5.1: Number of power, voltage and current limits violations per representative day. Fourth version of estimator based on voltage and current measurements, power cap for multiple vehicles on the section, charging priority based on direction and conditional charging on section 38

Parameter	Day 1	Day 117	Day 197	Day 200	Day 268	Day 305
Power	460	443	370	367	386	454
Voltage	0	3	4	0	0	0
Current	1060	448	471	501	732	927

vehicle on the section there is a specific decision process as the estimator can detect one vehicle only based on the I_σ concept, the decision process is the same for $N = 2$ as well as for $N = 5$. The ability to quantify the vehicles on the section is a crucial aspect which would make the estimations much more precise.

Day 1

From figure 5.3, it is evident that charging on section 38 did not pose a problem to substation 38. Section 38 in figure 5.4 obviously sometimes goes beyond the current limit. The power capacity potential of section 38 could have been much more utilized but even though the power limit is rapidly increased, it uses the same overhead lines topology as all the other sections. Because of that, the current is the limiting factor. The most significant improvement can be seen in the plot of SoC in figure 5.6. Charging on section 38 made sure every IMC trolleybus has enough energy to cover the day-long operation and all the vehicles cycle their batteries within the specified region of SoC.

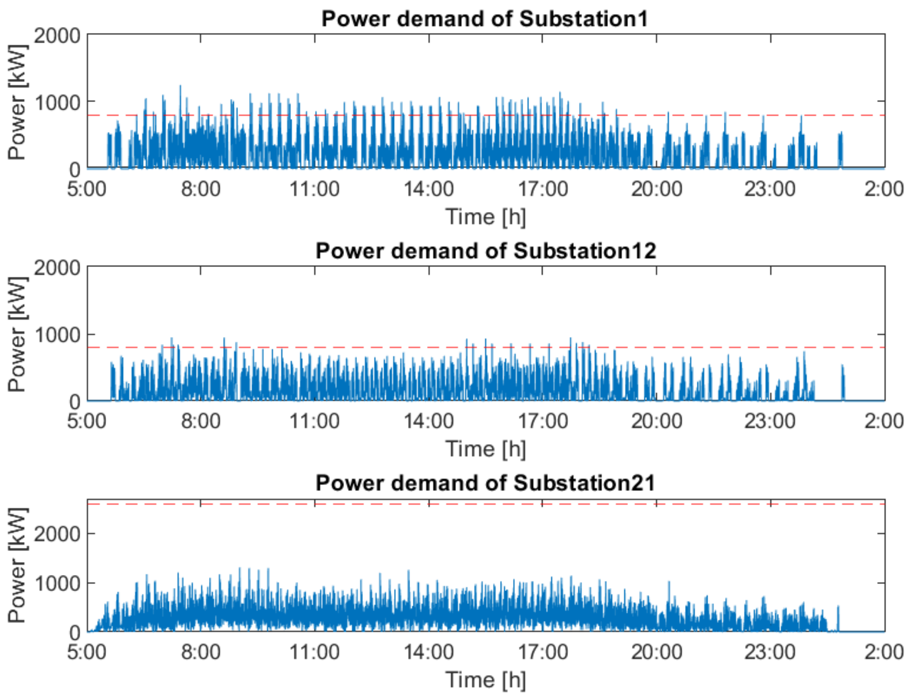


Figure 5.3: Substation power demand during **day 1**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

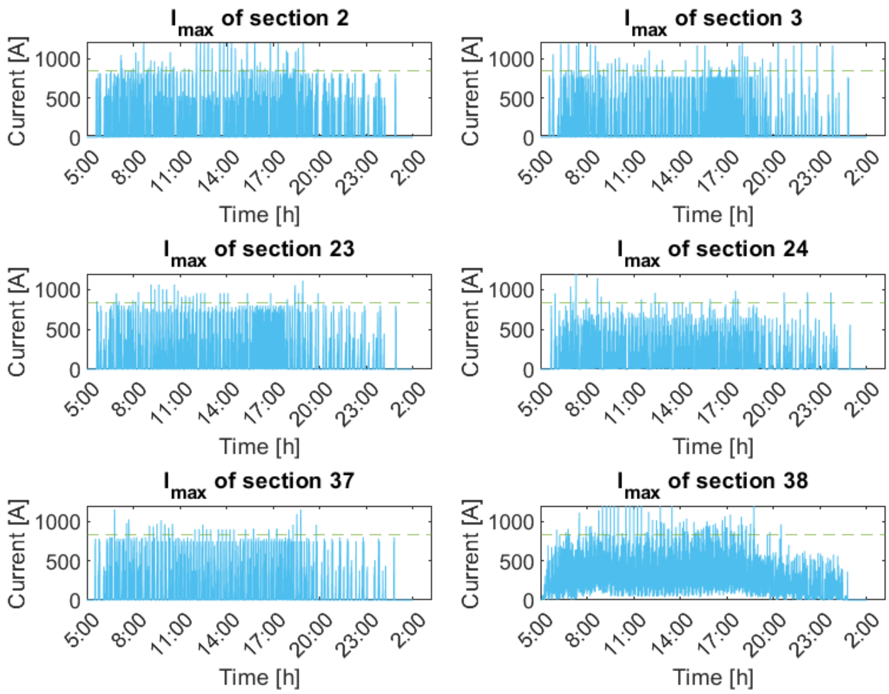


Figure 5.4: Maximal current on each section of line 352 route during **day 1**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

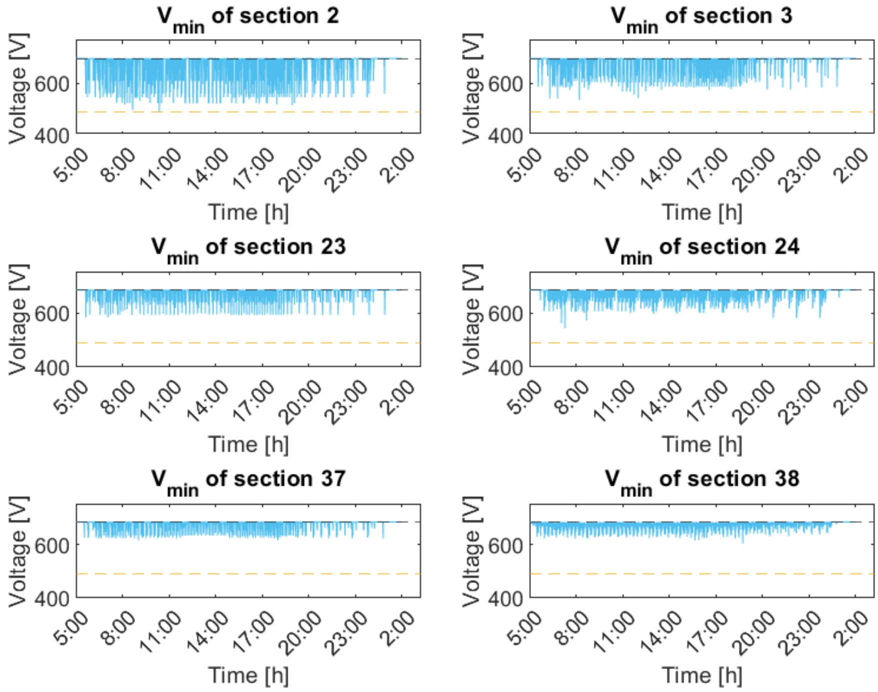


Figure 5.5: Minimal section voltage for each section of line 352 during **day 1**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

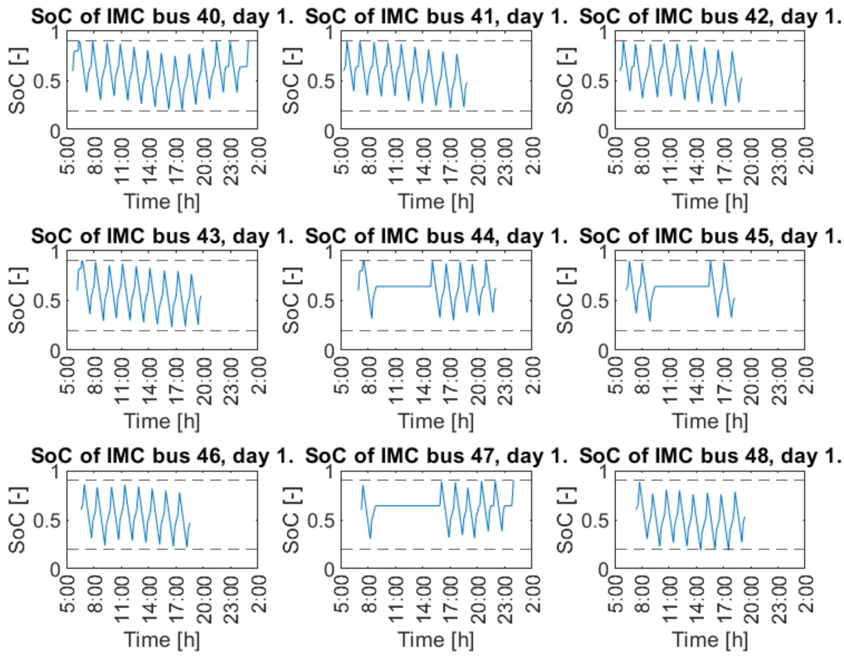


Figure 5.6: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 1**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Day 117

As day 117 is not that demanding in terms of traffic and energy consumption like for example day 1, the results are much more favorable. What is worth noticing is figure 5.10 with a plot of the SoC. The vehicles are more successful in charging higher powers than during day 1 and thus can collect more energy under the overhead lines. When they arrive at A station (section 38), the necessity of charging there is low. That is why vehicles either charge there for very short periods of time or they do not charge there at all. It reduces the number of current limit violations on section 38 as can be seen in figure 5.8.

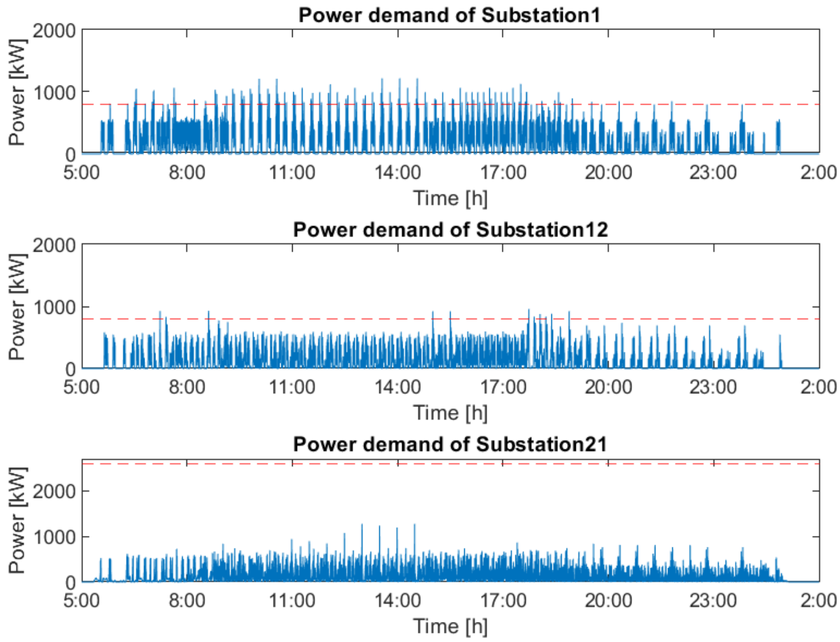


Figure 5.7: Substation power demand during **day 117**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

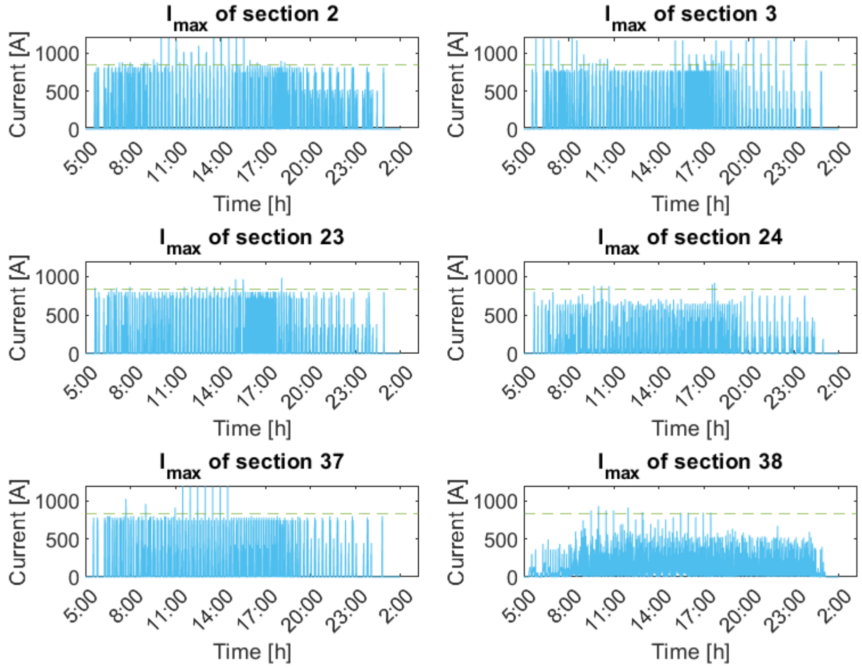


Figure 5.8: Maximal current on each section of line 352 route during **day 117**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

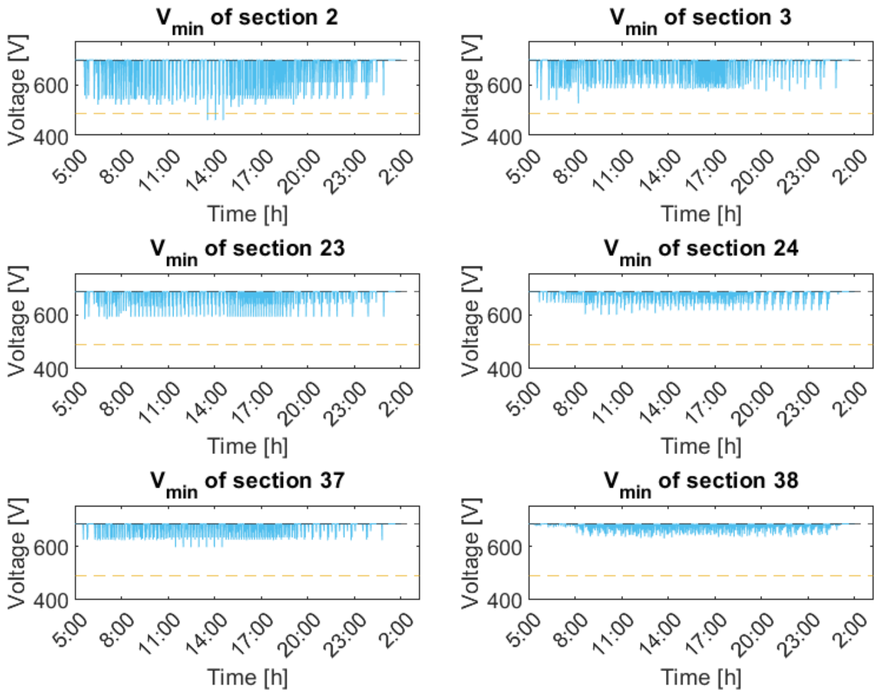


Figure 5.9: Minimal section voltage for each section of line 352 during **day 117**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

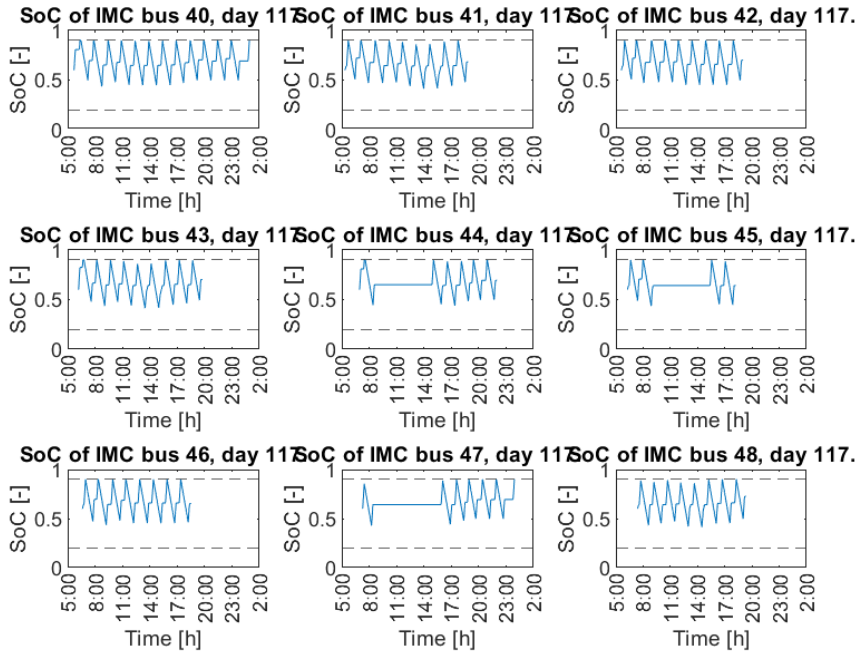


Figure 5.10: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 117**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Day 197

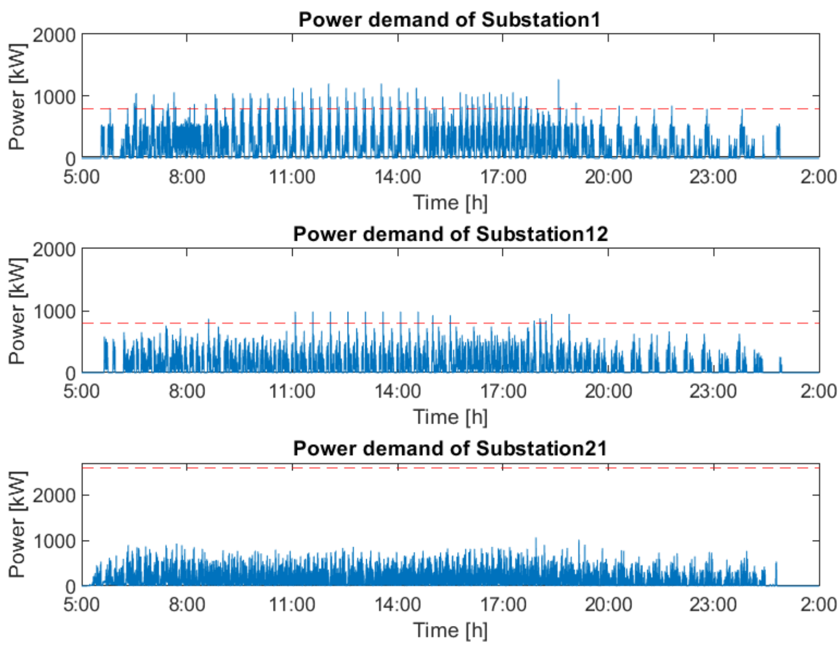


Figure 5.11: Substation power demand during **day 197**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

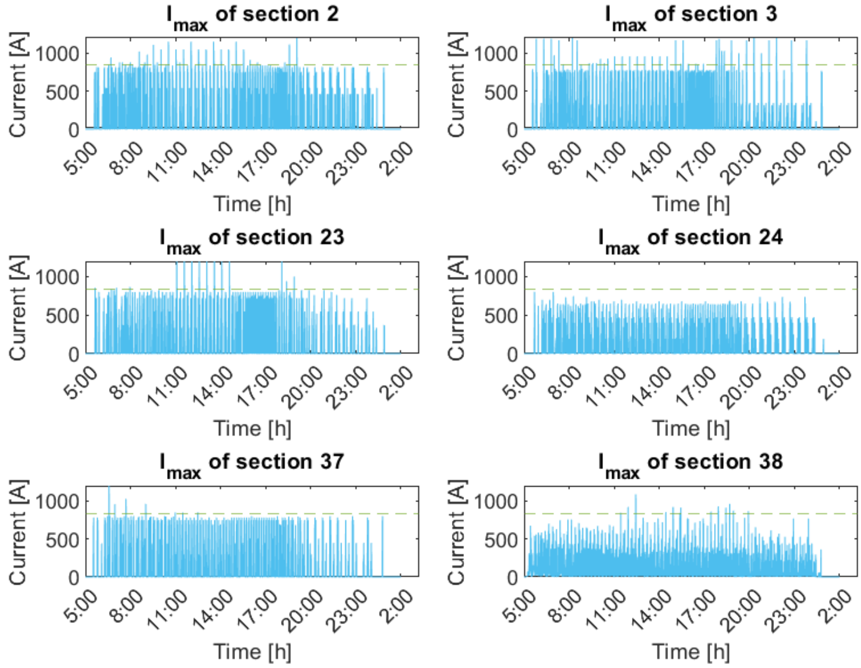


Figure 5.12: Maximal current on each section of line 352 route during **day 197**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

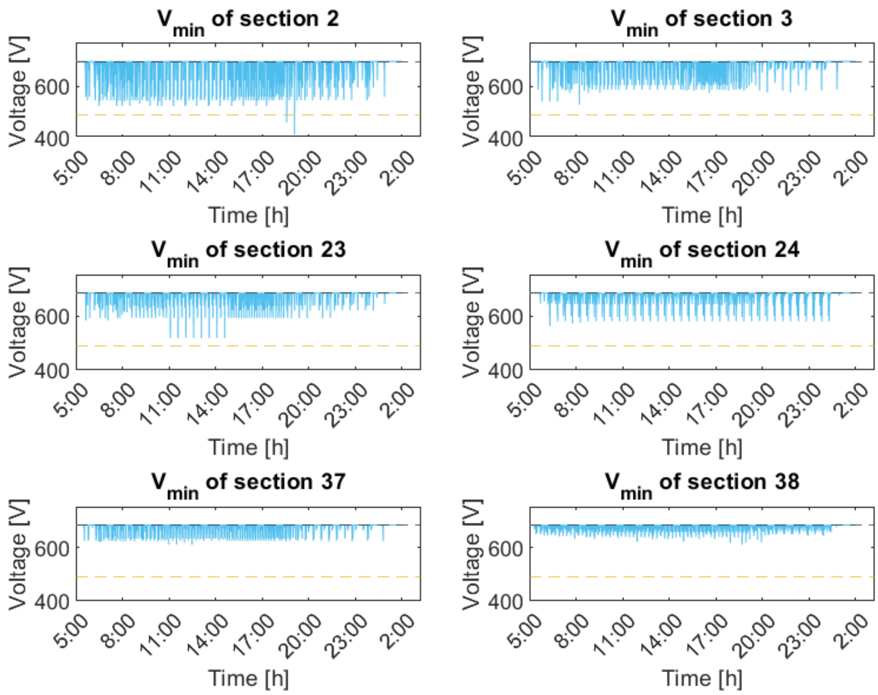


Figure 5.13: Minimal section voltage for each section of line 352 during **day 197**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

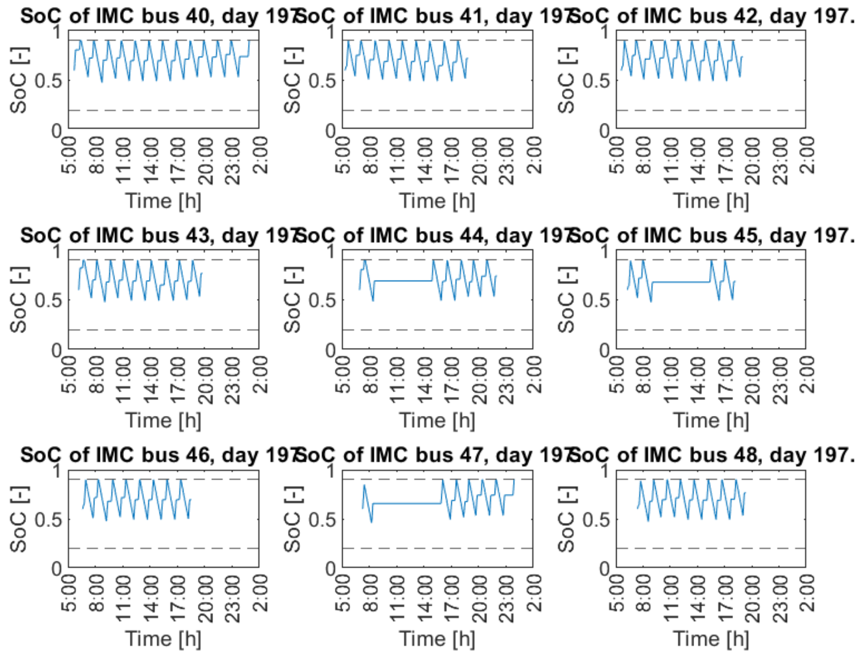


Figure 5.14: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 197**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Day 200

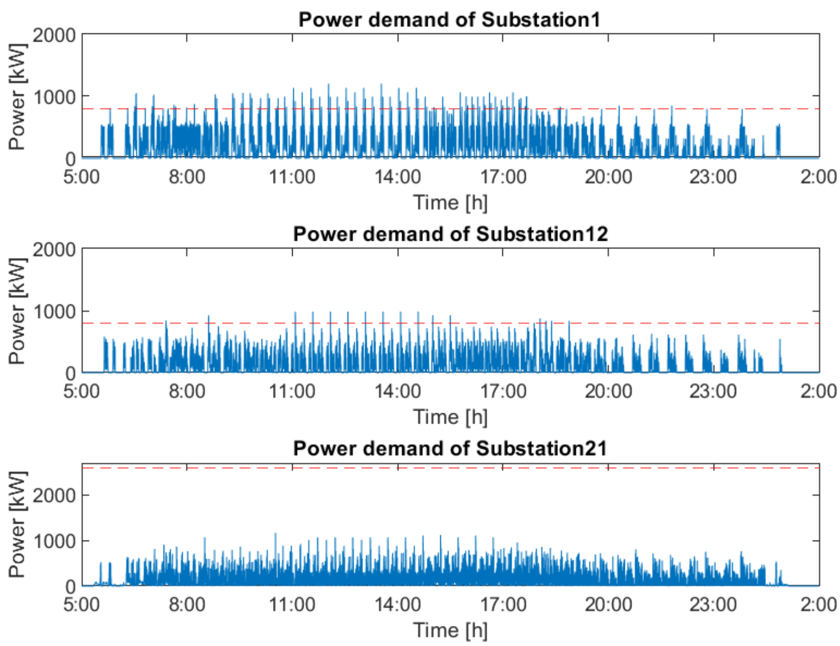


Figure 5.15: Substation power demand during **day 200**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

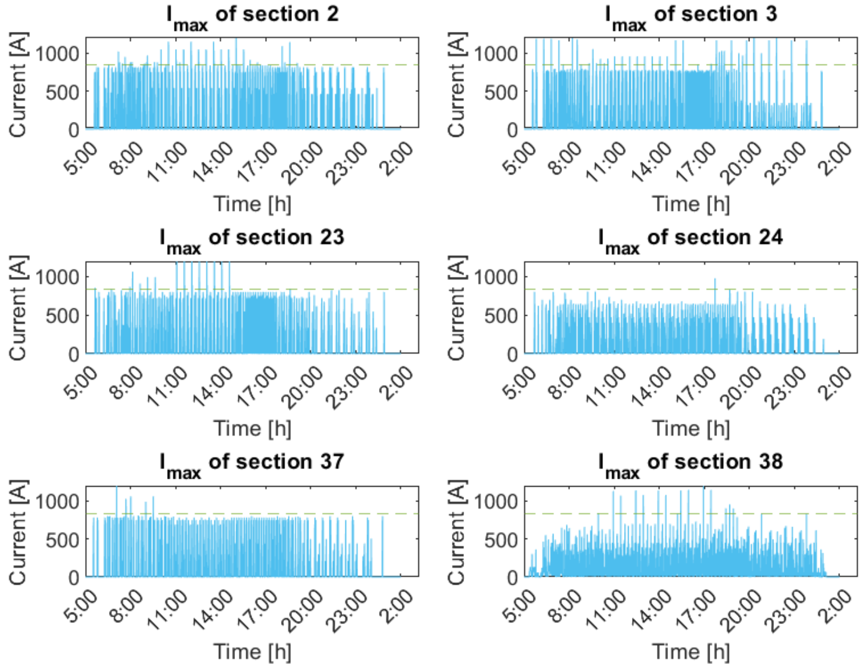


Figure 5.16: Maximal current on each section of line 352 route during **day 200**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

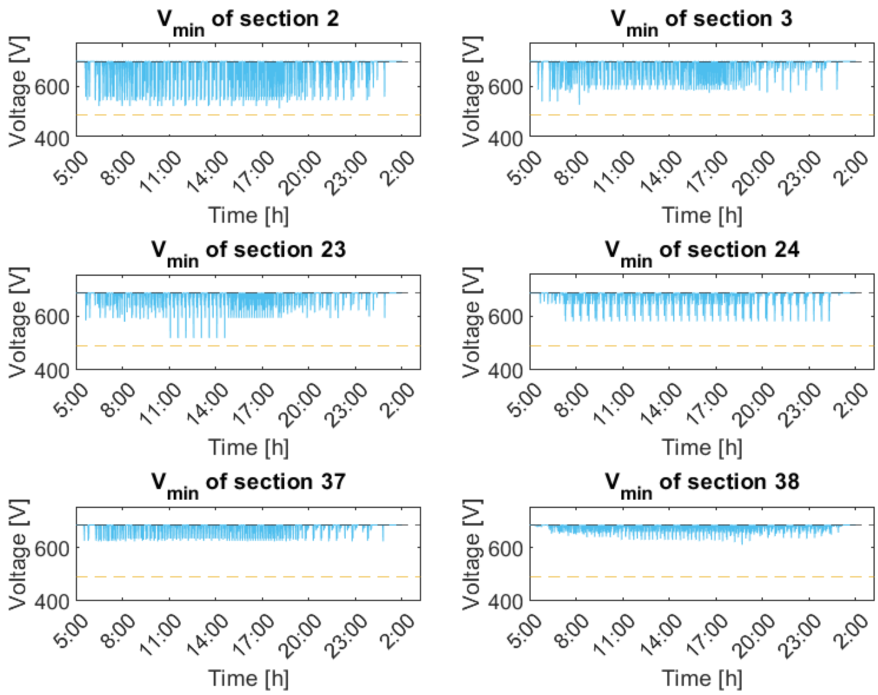


Figure 5.17: Minimal section voltage for each section of line 352 during **day 200**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

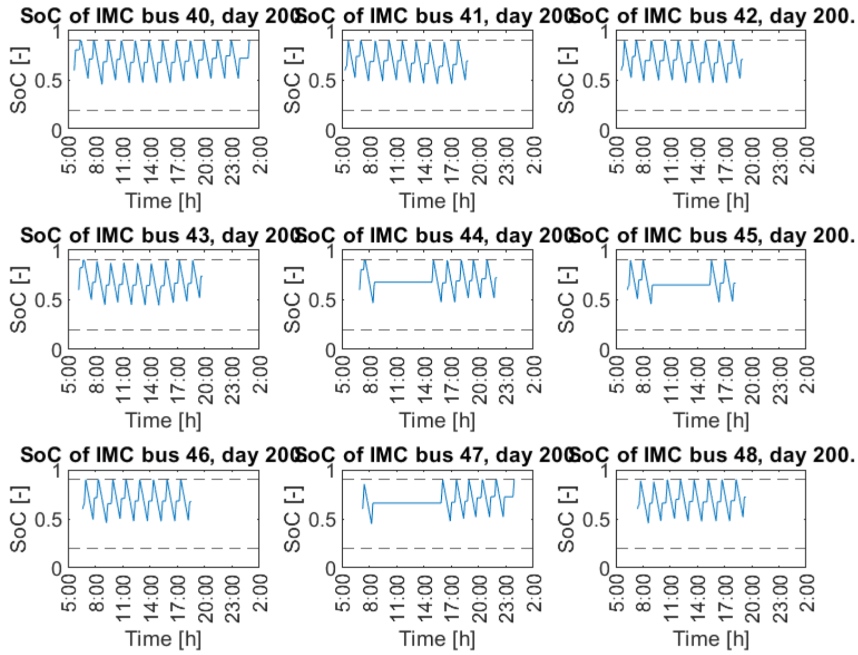


Figure 5.18: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 200**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Day 268

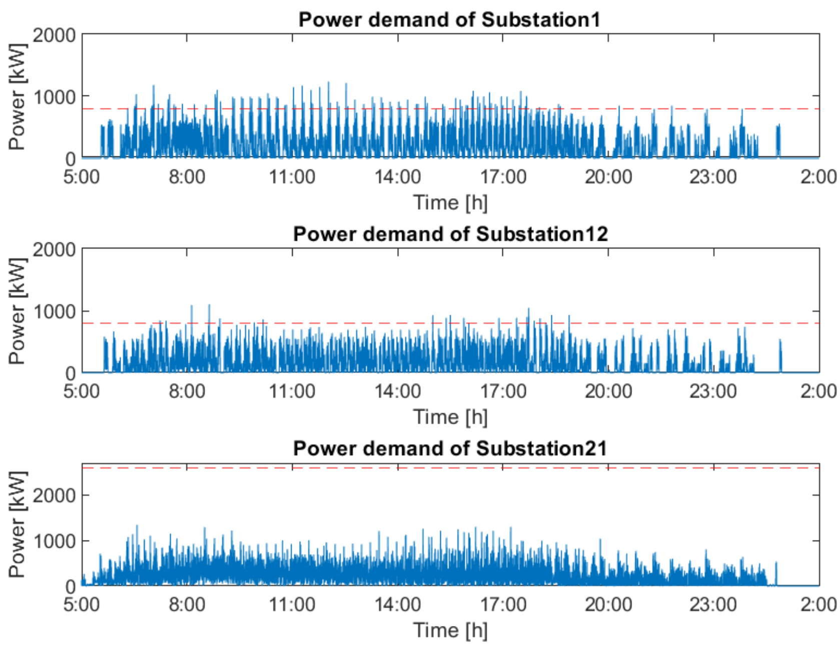


Figure 5.19: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

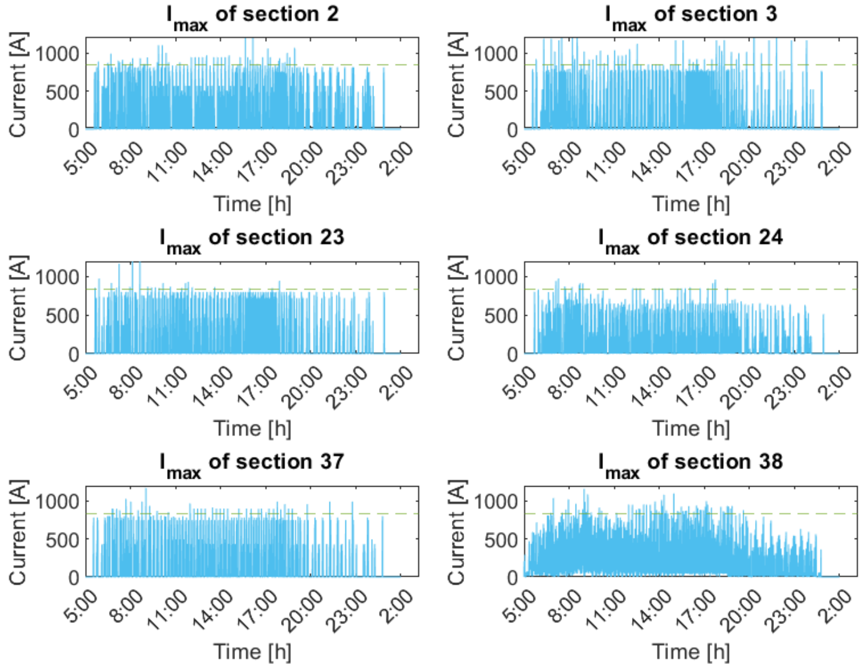


Figure 5.20: Maximal current on each section of line 352 route during **day 268**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

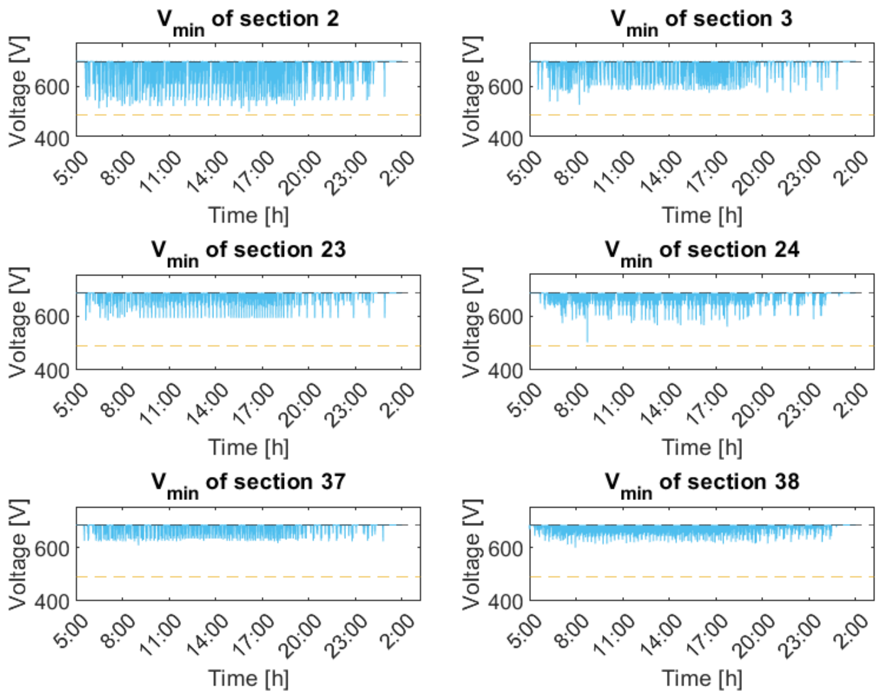


Figure 5.21: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

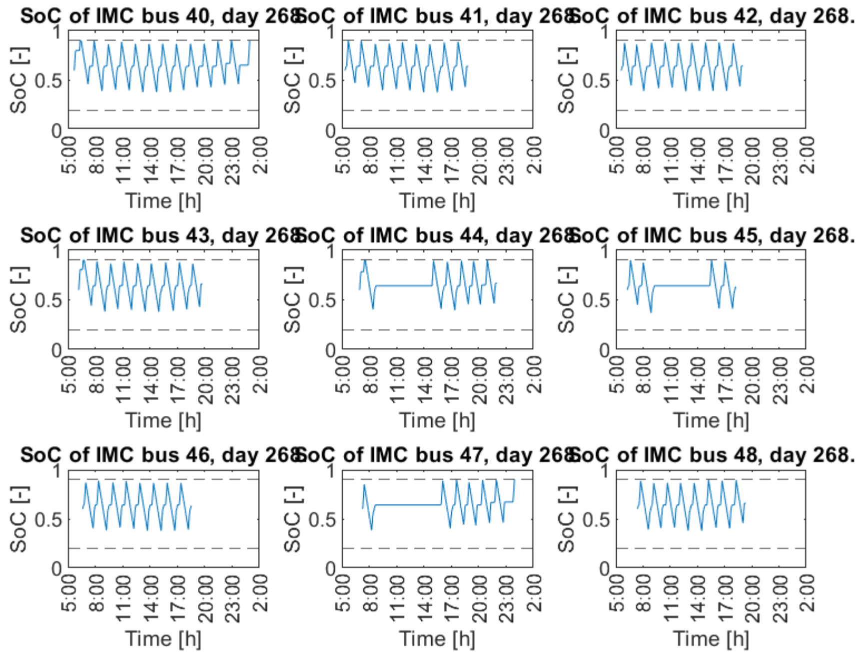


Figure 5.22: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 268**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Day 305

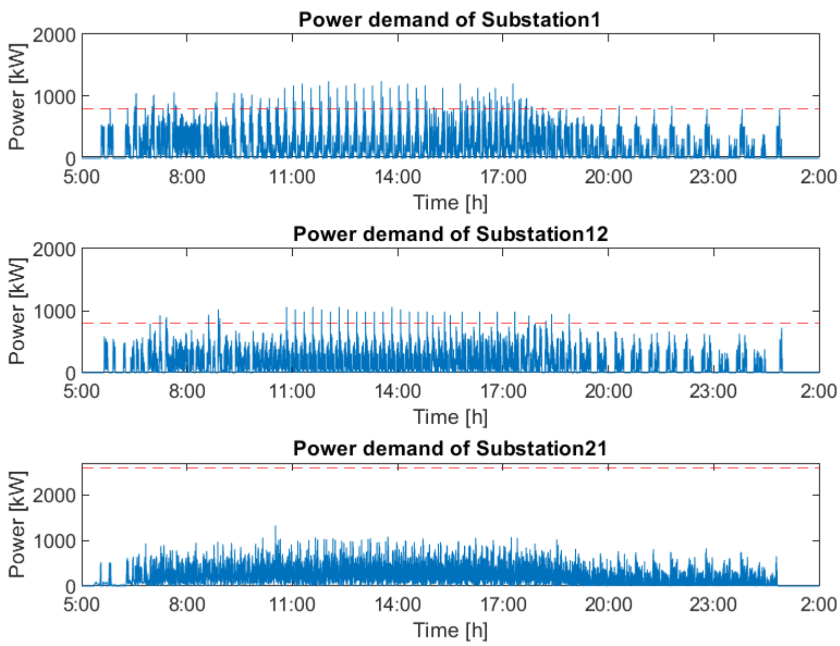


Figure 5.23: Substation power demand during **day 305**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V4 Scenario

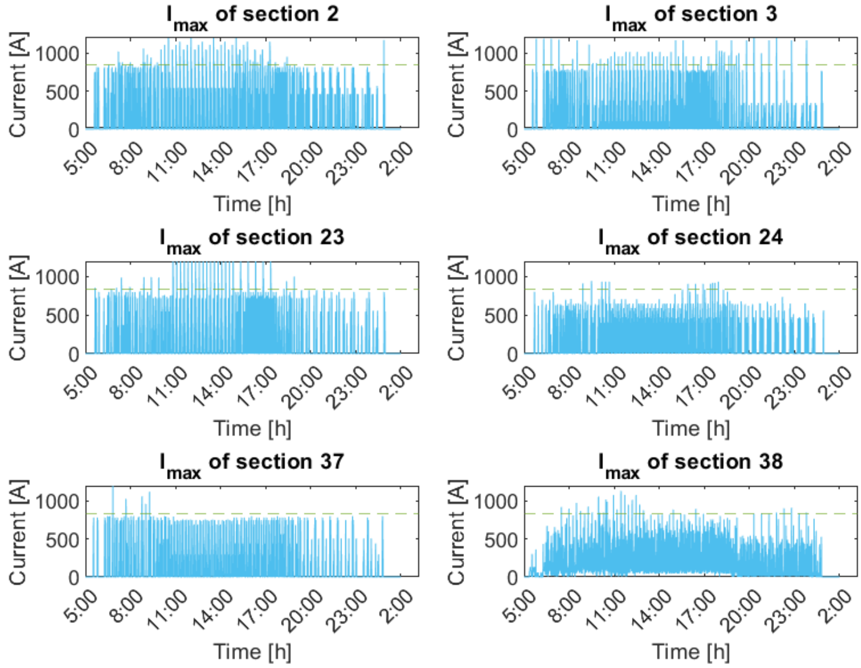


Figure 5.24: Maximal current on each section of line 352 route during **day 305**. Horizontal dashed green lines represent maximal allowed current in the overhead lines of 840 [A]. Estimator V4 scenario.

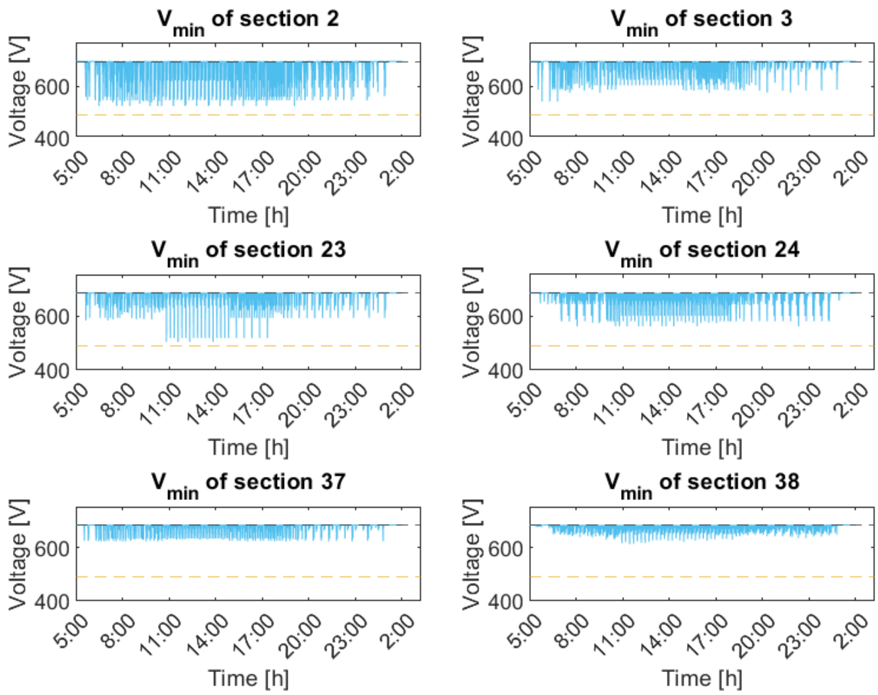


Figure 5.25: Minimal section voltage for each section of line 352 during **day 305**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V4 scenario.

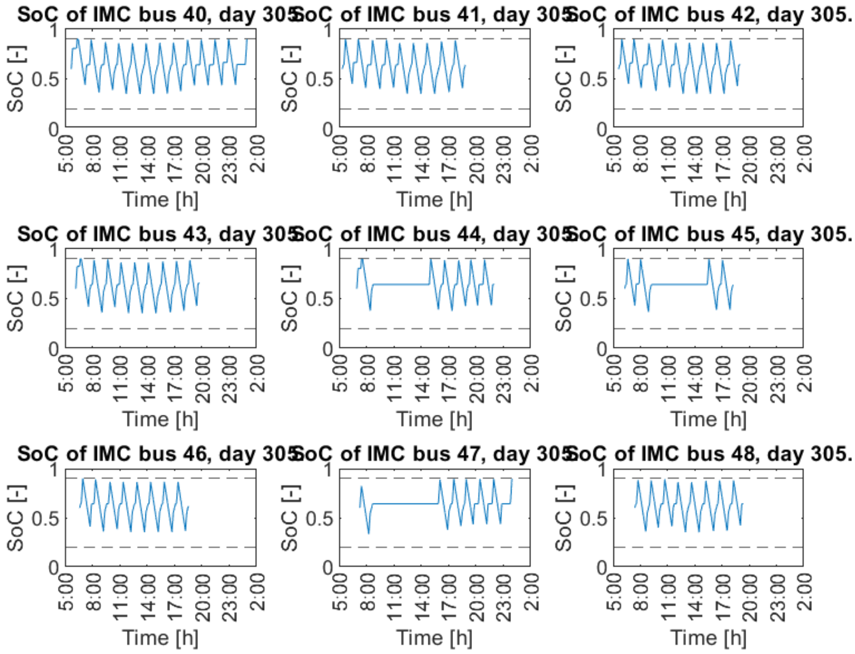


Figure 5.26: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 305**. Horizontal dashed black lines represent upper and lower limits of the SoC, 90% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V4 scenario.

Success Rate of Estimator V4

Following figure 5.27 shows the improvement in terms of the current violations by comparing the traffic in case of violation of estimator V2 and V4. The charging priority based on direction has a direct impact on reducing the number of limit breaches for 3-5 vehicles. These are exactly the traffic situations when just the traction power causes too much of a current in the overhead lines not even assuming charging power. By forcing the vehicles which have just entered the trolley-grid to charge low powers at all instances when the estimator senses the presence of another vehicle, space is made for other vehicles which are about to exit the trolley-grid to charge more and prepare for the autonomous part of the route. There is no change for 2 vehicles which means it is not a mistake of the estimator but of the circumstances on the section. As charging on section 38 was introduced, a slight increase in current limit violations can be spotted for high traffic which occurs there. The IMC vehicles are advised to charge 50 [kW] there and the sum of power demand of for example 10 vehicles might already result in high current. This proves the conditional charging based on the SoC of the IMC trolleybuses to be sensible idea as it prevents from more violations.

Figure 5.28 evaluates the success rate of the relationship between the bus voltage and the available power capacity $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$. The mismatch between this value suggested by the estimator and the actual power capacity that can be at that time provided by the substation is compared for estimators V2 and V4. These version differ in implementation of the charging priority based on direction. As a result, the aforementioned relationship is only used in one of the two directions. Therefore, the sizes of data sets differ and the histogram uses percentages for the purposes of the comparison. By implementing the charging priority, the power demand on sections decreased while multiple vehicles connected at the same time. The other vehicles either might have used this opportunity to maximize their charging power or to not change anything in case the power demand is already high enough. If it was only for the decrease of demand, the voltage drop would be smaller and the accuracy of the relationship would be better as it increases with proximity to nominal substation voltage. As it could have gone either ways, the effect is not that significant on the mismatch. A slight shift to the left could still be observed meaning a mismatch of lower magnitude was more common with V4.

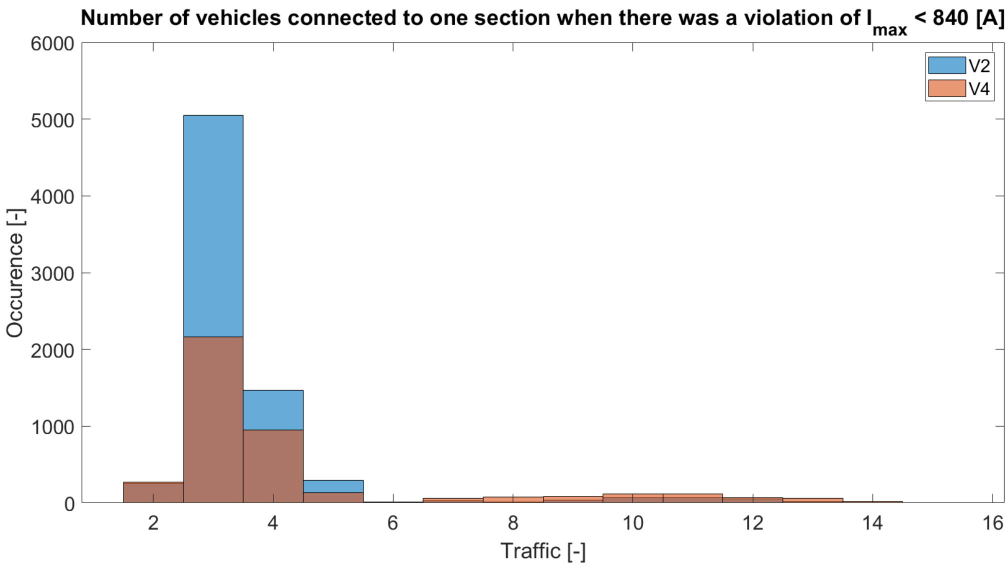


Figure 5.27: Histogram of traffic when the limit of 840 [A] was violated. Cumulative data for all IMC trolleybuses and all simulated days. Estimator V2 scenario vs. estimator V4 scenario. Decrease of total violations with 2-5 vehicles, increase of violations with 8+ vehicles due to charging on section 38.

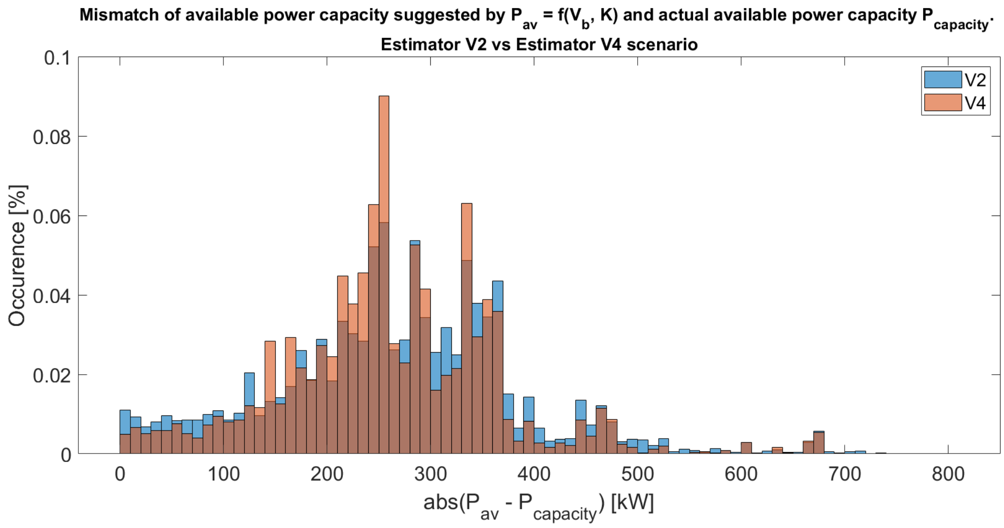


Figure 5.28: Comparison of mismatch of available power capacity suggested by $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$ and actual available power capacity P_{capacity}. Cumulative data for all IMC trolleybuses and all simulated days. Results presented in percentage as the sizes of the data sets differ. Estimator V2 vs Estimator V4 scenario

One reason for the relationship $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$ occasionally giving rather large mismatch is the conservative value of K. The fact that the suggested power capacity has to be found in at least 95% of the historical cases is prone to an error. Also, the relationship could take the position of the IMC trolleybus into account as another decision layer. A better understanding of how the position affects the voltage would help to achieve better accuracy. The increase of occurrence between 200 [kW] and 300 [kW] mismatch can be justified by using the charging priority based on direction. After entering the trolley-grid from battery mode, the power demand of the trolleybus is limited which gives space for other vehicles to draw more power. As the K probability is very conservative, even though there is now power capacity available, the relationship rules to draw a conservative charging power.

This last version of estimator can be compared with the previous ones regarding the proximity to the Best Case scenario. Such comparison can be seen in figure 5.29 which depicts power demand on substation 1 on day 1. While versions 1 and 2 used only few constraints and did not get very close to the curve of Best Case scenario, version 4 of estimator is the most accurate. It also worked appropriately to decrease the magnitude of the power demand peak. However, it is evident that not even the latest version of estimator is not accurate enough to provide the optimal results.

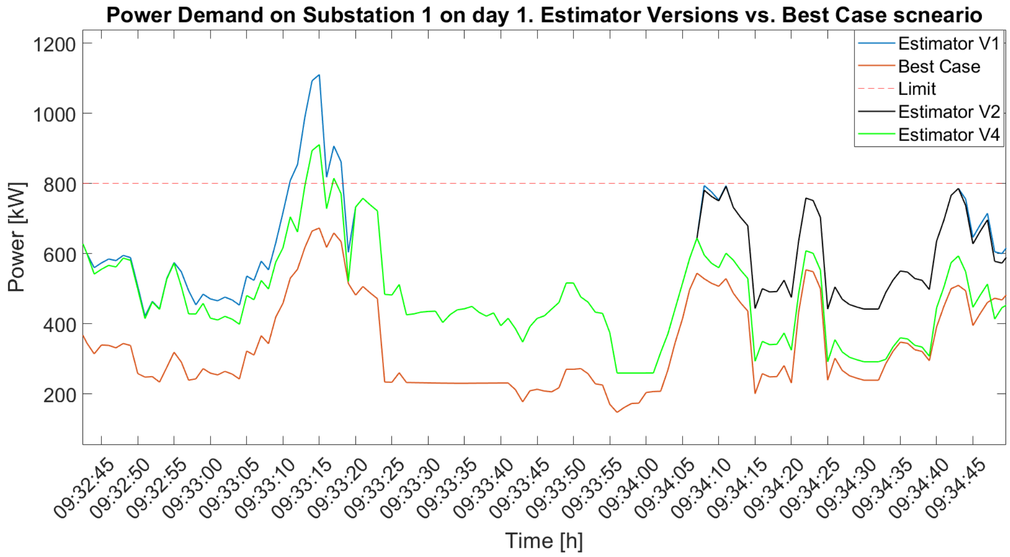


Figure 5.29: Power Demand on substation 1 on **day 1**. Comparison of Estimator versions vs. Best Case scenario

Energy Collected

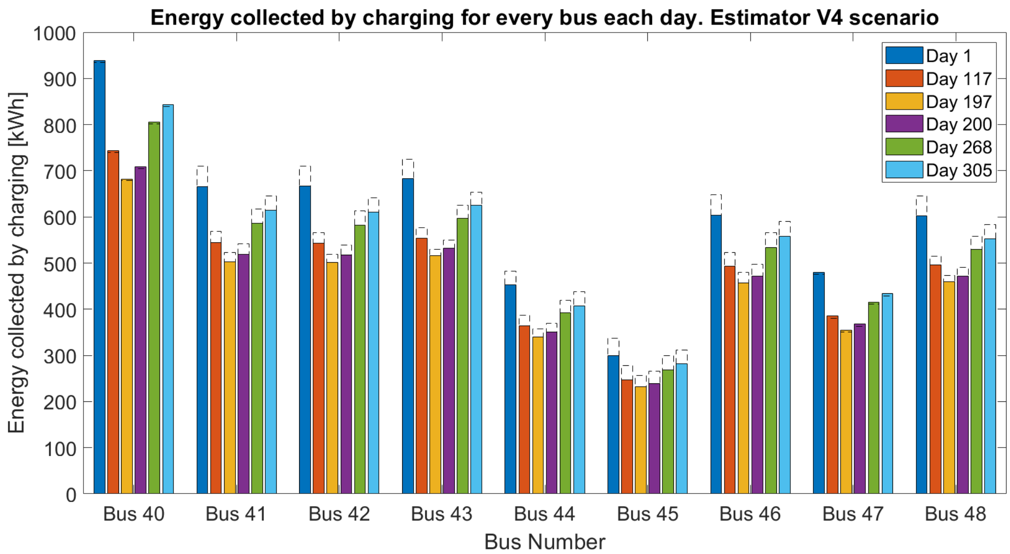
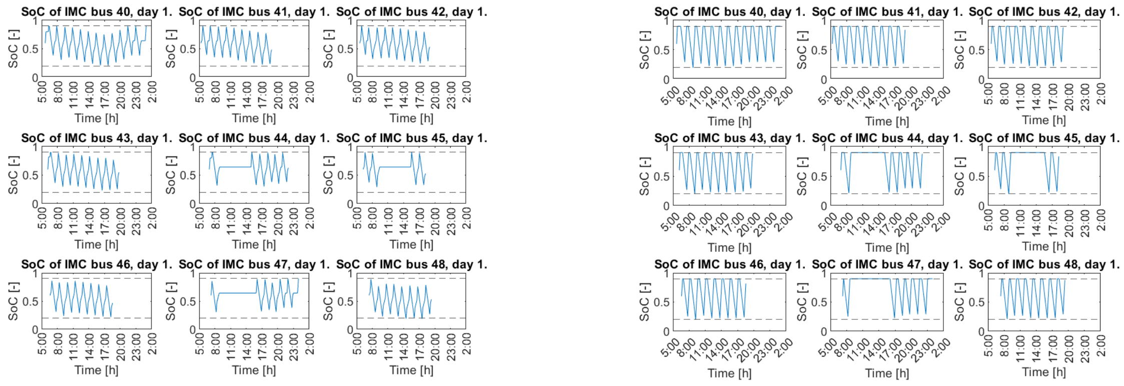


Figure 5.30: Energy collected by every bus each representative day of the year. Dashed transparent bars represent the potential energy to be collected. Estimator V4 scenario.

Version 4 of the estimator was finally able to come close to the amount of energy collected by the Best Case scenario which is represented by dashed transparent bars in figure 5.30. Especially Bus 40 equaled the performance of the Best Case scenario. Other buses collected a little less energy. The reason for that can be seen from the plots of the SoC curves in 5.31. Whereas with the Best Case scenario all the IMC trolleybuses reach full SoC of their on-board batteries, the Valley-Charging approach supported by estimator sometimes fails to manage so.

All the plots of energy collected by a particular charging scenario show that charging on section 38 is absolutely necessary for integrating the IMC trolleybuses on line 352. Due to its long stopping time of several minutes there, the charging potential is undoubted. On top of that, it was proved that charging rather safe value of 50 [kW] might be enough even though the Best Case scenario with perfect communication sometimes allowed for higher charging powers.



(a) Valley-Charging

(b) Best Case

Figure 5.31: Comparison of SoC of IMC trolleybuses with Valley-Charging with estimator approach and Valley-Charging with communication approach (Best Case scenario). Buses 44, 45 and 47 only operating in the morning and evening. Data for 1.1.2020 (day 1)

5.2. Comparison of IMC charging approaches

The Valley-Charging scheme which varies the charging power according to the state of the grid is an innovative approach but only exists on a research level. IMC systems are currently using conventional charging schemes which can only make use of two charging powers, one for when the vehicle is moving and one for when the vehicle is standing. Not only might these charging approaches be insufficient for collecting enough energy because they are not utilizing the potential of the trolley-grid in the fullest but when the charging power is constantly high and there is no mechanism to react to the signals (measurements) from the trolley-grid, there might be too many violations.

To compare the results of the Valley-Charging approach, the conventional charging schemes of:

Ψ [kW]	Π [kW]
240	200
150	100
120	90
90	60

where Ψ stands for charging power in-motion and Π for charging power standstill, were run for day 1. Table 5.2 shows the results of each simulation in terms of the energy collected per section in [kWh]. To make the schemes comparable, all schemes use charging 50 [kW] on section 38 (A station) as the Valley-Charging does. Unlike the Valley-Charging, other charging schemes do not rely on the SoC condition explained earlier in section 5. Each scheme was also evaluated in terms of the substation power demand violations. It may happen that the conventional charging scheme is not suitable for any section/substation. There just might be too many violations of the limits as well as the breaches might be too severe. If that is the case, there is 'X' in the table and the energy collected on such section is not taken into account. For 240/200, the constant charging of high powers is not a viable option. It would both overheat the overhead lines by excessive current and damage the substations with high power demand. This charging scheme cannot be used without any control mechanism. It is the first benefit of the Valley-Charging approach which successfully uses these high charging powers at times when the situation at the trolley-grid allows to. Just like this, it helps utilize the trolley-grid better.

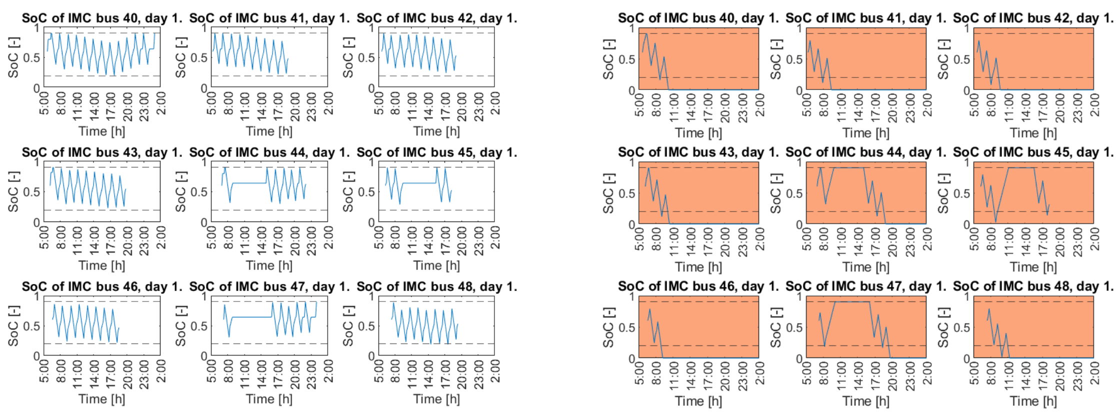
Charging scheme of 150/100 could be used for substation 21 feeding sections 37 and 38 among others. The 120/90 is suitable without serious problems for substation 12 (sections 24 and 23). As could be seen in the results presented so far, substation 1 and its sections 2 and 3 were the most problematic ones and they can do only with 90/60 constant charging scheme. Previous researches introduced an Adaptive charging scheme. It is based on selecting the suitable charging scheme for each section involved. In this case, the Adaptive charging scheme looks like this:

Section	24	23	2	3	37	38
Charging scheme [kW]	120/90		90/60		150/100	

Table 5.2: Energy collected per section based on a charging scheme. Charging schemes have format [Ψ;Π] (Charging power in-motion/Charging power standstill) in [kW]. 'X' represents the charging scheme not being usable on the section. Adaptive charging uses the highest charging scheme available for that section. Data from 1.1.2020

Charging Scheme	Energy Collected per Section [kWh]						Total [kWh]
	24	23	2	3	37	38	
240/200	X	X	X	X	X	X	0
150/100	X	X	X	X	464	1531	1995
120/90	427	503	X	X	378	1562	2839
90/60	318	379	467	498	280	1595	3537
Adaptive Charging	427	504	466	494	467	1574	3932
Valley-Charging	753	905	897	1073	640	1126	5393

Table 5.2 also shows the total energy collected by a charging scheme. The Valley-Charging approach allows the IMC vehicles to collect almost 1400 [kWh] more of energy than the Adaptive charging scheme. Unlike the Valley-Charging approach which can provide enough energy to make a day-long operation, the Adaptive charging scheme fails to collect enough energy and the batteries get depleted very fast (figure 5.32). This happens because the adaptive charging scheme fails to collect enough energy for the round trip and the vehicle is compensating for this shortage by depleting the battery. Using high charging powers of 240/200 [kW] at the convenient moments is essential to operate line 352 with IMC trolleybuses which collect enough energy and do not represent a threat for the trolley-grid at the same time. No conventional charging scheme based on two charging powers nor the adaptive scheme could manage the energy demand on the autonomous part of the route which is around 72 [kWh] on 28.8 [km].



(a) Valley-Charging (b) Adaptive Charging

Figure 5.32: Comparison of SoC of IMC trolleybuses with Valley-Charging approach and with Adaptive Charging approach. Buses 44, 45 and 47 only operating in the morning and evening. Day 1

Table 5.3: Number of power, voltage and current limits violations per charging scheme. Numbers in the parenthesis represent critical violations which are greater than 150% of the power limit or voltage below 400 [V]. Violating Energy shows [kWh] of energy when the substation power is above 800 [kW]. Last line of the table shows ratio of [kWh] of total operational transmission losses to [kWh] of total energy stored in battery. Charging schemes have format Ψ/Π (Charging power in-motion/Charging power standstill) in [kW]. Adaptive charging uses the highest charging scheme available for that section. Adaptive charging scheme is not able to collect enough energy (only 55%) and would make line 352 inoperable. Valley-Charging is successful as it can collect 106% of energy needed. Day 1

Parameter	Valley-Charging	Adaptive	240/200	150/100	120/90	90/60
Power violation	460 (2)	70 (0)	890 (30)	213 (1)	123 (1)	69 (0)
Voltage violation	0	6 (0)	92 (15)	28 (0)	15 (0)	6 (0)
Current violation	1060	932	4184	1728	1138	871
Violating Energy [kWh]	116	12	469	98	43	11.4
$\frac{[kWh]E_{\mathrm{P>800}}}{[kWh]Energy}$ [%]	2	0.3	N/A	5	1.5	0.3
$\frac{[kWh]Loss}{[kWh]Energy}$ [%]	5.6	4.6	7.7	5.2	4.8	4.6

Table 5.3 compares the charging schemes next to each other in terms of the violations of power, current and voltage limits for day 1. There are two numbers for the power limit; the first one is the total amount of violations according to the limits described in section 3.1 and the numbers in the parenthesis represent severe violations that would cause serious damage to the infrastructure of 150% of the initial limit value. Naturally, the conventional charging scheme of 240/200 happened to have the most violations of all, with 15 occasions when the voltage would make the trolley-grid momentarily out of operation. The amount of violations of the Valley-Charging scheme is somewhat comparable to the violations of either 120/90 or 150/100 conventional charging schemes. Considering the fact that the Valley-Charging scheme also allows charging enough energy to make line 352 operable, it is superior to the others. While 120/90 achieving the same amount of current violations as the Valley-Charging scheme, it can secure 2600 [kWh] less energy providing only 55% of the total energy required to make line 352 operable.

The Valley-Charging approach breaches the substation power demand by more than 150% twice. However, it is necessary to mention that both of these violations are caused by multiple vehicles on sections 2 and 3 which share substation 1. It is out of the capability of the estimator to predict conditions on both sections and thus the suggestion of charging power might be wrong. If the limit is lowered to 120% which is undesired continuous power demand, the total number of violations would be 117. 70% of the cases are caused by this described phenomena and are technically not a mistake of the estimator. The results have shown that without communication between the vehicles and the infrastructure, these situations of multiple vehicles connected to two sections fed by one substation would see power demand violations.

Another perspective is offered in the second part of the table. For each charging scheme, there is the amount of [kWh] of energy provided by the substation when the substation has to supply more than 800 [kW] and thus violating the limit. This factor can be translated into the severity of the violations. Even though the number of violations over 800 [kW] is more than double for Valley-Charging compared to 150/100 approach, this factor is comparable. It means that Valley-Charging has less severe violations peaking just above 800 [kW]. At the same time, 150/100 cannot collect enough energy while Valley-Charging can secure enough energy. This value can also serves to study the ratio of energy collected when violating the power limit and total energy collected. The 150/100 scheme even collects more energy while violating the limit than the Valley-Charging does. They are also similar in terms of ratio of [kWh] of transmission losses to total energy collected.

Figure 5.33 shows the comparison of duration and severity of substation power demand while there was violation. It can be noticed that the conventional 240/200 not only causes much higher peaks of power demand but also the duration of the violation is longer, up to 18 [s]. The Valley-Charging is comparable to the 150/100 scheme and decreases both the severity of the violations and their duration

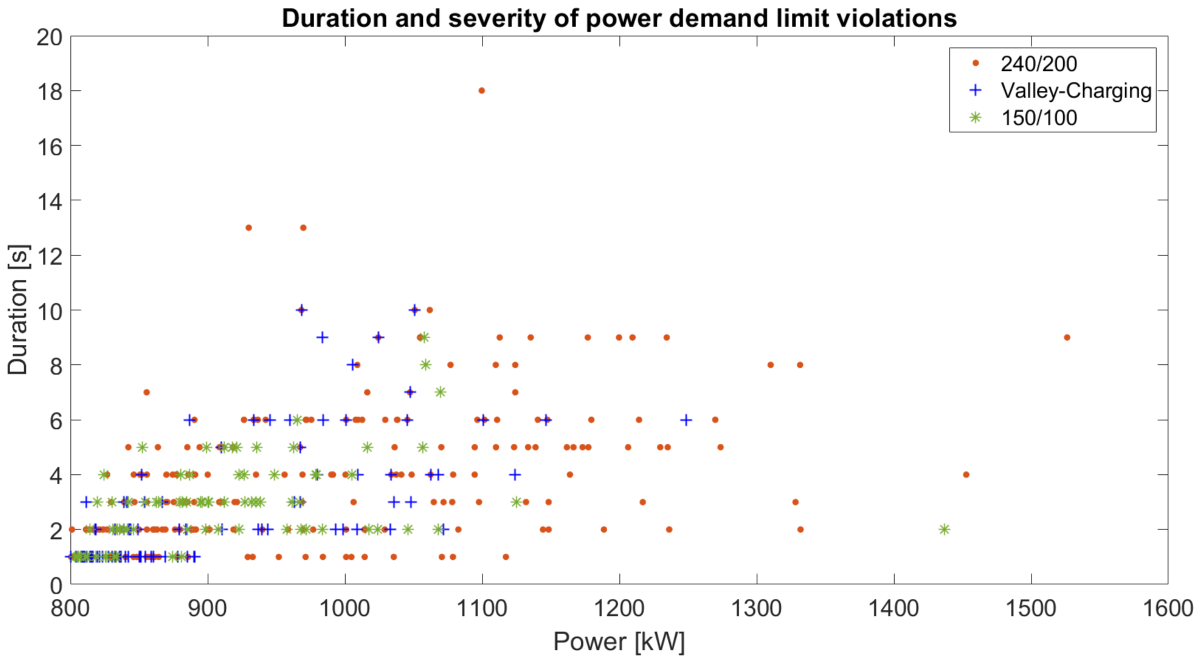


Figure 5.33: Duration and severity of power demand limit violations

also. A lot of blue markers corresponding to the Valley-Charging approach can be spotted between 800-900 [kW] region with just 1 [s] duration. That makes them occasional minor peaks which do not pose any threat to the substation.

Table 5.4: Comparison of conventional charging scheme, adaptive charging and Valley-Charging presented in this thesis in terms of the feasible energy collected by charging per round-trip and the necessity of opportunity charging at the End of Line (EoL) in Wageningen. Total Round-trips stand for the average amount of round-trips the IMC trolleybuses can make before depleting the battery. Adaptive covers 21/71, Valley-Charging covers 71/71. Energy Collected per round trip determined by the total energy collected from table 5.2 divided by average amount of round-trips, 71. Where 240/200 and adaptive charging schemes need an opportunity charger in Wageningen to make line 352 operable, Valley-Charging approach does not require opportunity charging. Line 352. Day 1

Line **352**			Energy for autonomous trip: **72 [kWh]**					
Total Round-trips			Feasible Energy Collected per Round-trip			Extra time needed for opportunity charging of 100 [kW] at off-grid EoL		
240 200	Adaptive Charging	Valley Charging	240 200	Adaptive Charging	Valley Charging	240 200	Adaptive Charging	Valley Charging
0	21	71	0 [kWh]	55 [kWh]	76 [kWh]	**43 [min]**	**10 [min]**	**0 [min]**

It has been shown how the conventional charging schemes are not sufficient in terms of the energy collected to make line 352 operable. When they are deployed anyway, the lack of energy has to be compensated for by opportunity charging at one of the end stations of the line. Opportunity charging can be described as battery charging for rather short periods of time, typically minutes, multiple times a day. Usually, vehicles are using opportunity charger when idling at the end of the line in case of public transport or on highway rest stations in case of a personal car. For public transport vehicles, opportunity charger significantly reduces the urgency to stop for depot charging and prolongs the time they can operate. On the other hand, it requires investment in the opportunity charger infrastructure on places such as the end of line.

If the economical investment necessary to build the new infrastructure is omitted, it significantly cuts from the advantage of the whole IMC concept which is charging en route and not having to stop for charging. Table 5.4 provides a comparison of the conventional charging scheme of 240/200 [kW], adaptive charging and Valley-Charging presented in this thesis and how long opportunity charging of 100 [kW] would they need to be operable on line 352. As the autonomous part out of the trolley-grid is rather long on line 352, it requires 72 [kWh] of energy on average to cover it. The 240/200 scheme as well as the adaptive charging scheme can pick-up 0 [kWh] and 55 [kWh], respectively, under the overhead lines per round-trip. Valley-Charging can collect 76 [kWh] on average. These values of energy collected per round trip were determined by dividing the total energy collected from table 5.2 by an average amount of round trips per day, which is 71. It would take at least 43 [min] for 240/200 scheme which would have to charge the whole amount of energy at the opportunity charger. Adaptive charging would have to consider 10 [min] delays of its IMC trolleybuses to charge the approx. 17 [kWh] more for every round-trip. Without opportunity charger, adaptive charging scheme is not capable of collecting enough energy. Because the Valley-Charging can operate without the opportunity charger and service all 71 round-trips, it provides a significant stopping time reduction. Not only it saves on the infrastructure costs but also the trolleybus fleet size can be smaller as they all can operate at the same time with no bus idling at the opportunity charger.

5.3. Adaptability of estimator-supported Valley-Charging

One of the largest promises of the Valley-Charging approach with the state of the grid estimator is its capability to react to unexpected circumstances in traffic. When using a conventional charging scheme without any form of control of the charging power, there is no power flexibility and the operation might not be feasible in case of exceptional conditions such as traffic jams, trolleybus delays or infrastructure changes. On the other hand, the estimator should sense these changes and adjust the charging power as accurately as possible to prevent from failures. Like this, it is easier for the trolley-grid to integrate new technologies such as EV chargers or to for example adapt to change of routes due to maintenance.

5.3.1. Traffic Delays

Public transport is a stochastic system that is prone to frequent delays. According to the public transport schedule, the trolleybuses should not meet in large numbers at the same time as it could be demanding for the substation. With delays, this circumstances can occur. Conventional charging scheme could not react to it and could damage the infrastructure resulting in disconnecting the substation from feeding the section. The Valley-Charging approach is hoped for adapting to it and mitigating the congestion at the trolley-grid. To test it, the data sets corresponding to each bus used for simulating the trolley-grid were randomly shifted in interval <-2;20> [min] to account for possible traffic delays.

Following two figures show the severity of randomization in terms of the traffic that each IMC trolleybus experiences throughout the day. Whereas vehicles on day 1 (figure 5.34) see a normal difference in the traffic, some trolleybuses on day 268 (figure 5.35) experience absolute change of their schedule, especially trolleybus 43. For some vehicles, like trolleybuses 41, 42 or 46 on day 1, is the new ”delayed” schedule actually better than the initial as the amount of occasions when they happen to be alone on a section increased.

Figures 5.36 and 5.37 show a comparison of SoC of all the IMC vehicles for the initial data set and the randomized one for days 1 and 268, respectively. When studying the histograms of traffic and the SoC curves, a pattern emerges. Those IMC trolleybuses which happened to experience more times of alone operation or low traffic operation, did not see drops in their SoC which is now more stable. On the other hand, all those vehicles for which the amount of times of single operation decreased might either see lower levels of SoC or might even experience inoperable conditions. On day 1, both trolleybuses 41 and 42 spent more time alone on section which allowed the estimator to suggest charging higher powers. As a result, their SoC is not gradually decreasing as with the initial data set. Trolleybus 43 on day 268 was almost never connected alone on a section. It could not collect the same amount of energy and its SoC rapidly dropped at the end of the day.

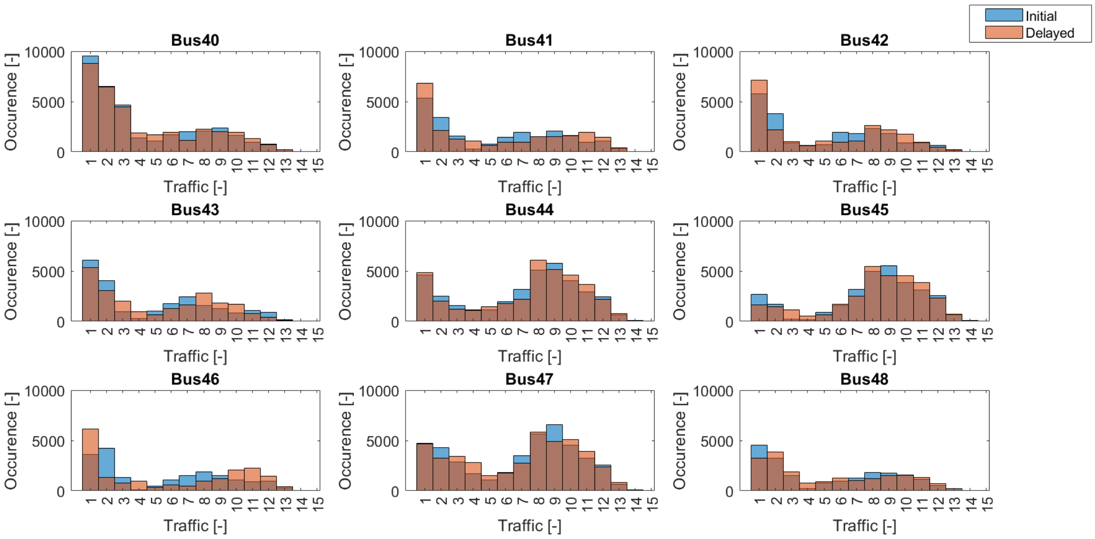


Figure 5.34: Traffic per IMC trolleybus. Comparison of initial data set and delayed traffic data set. Day 1

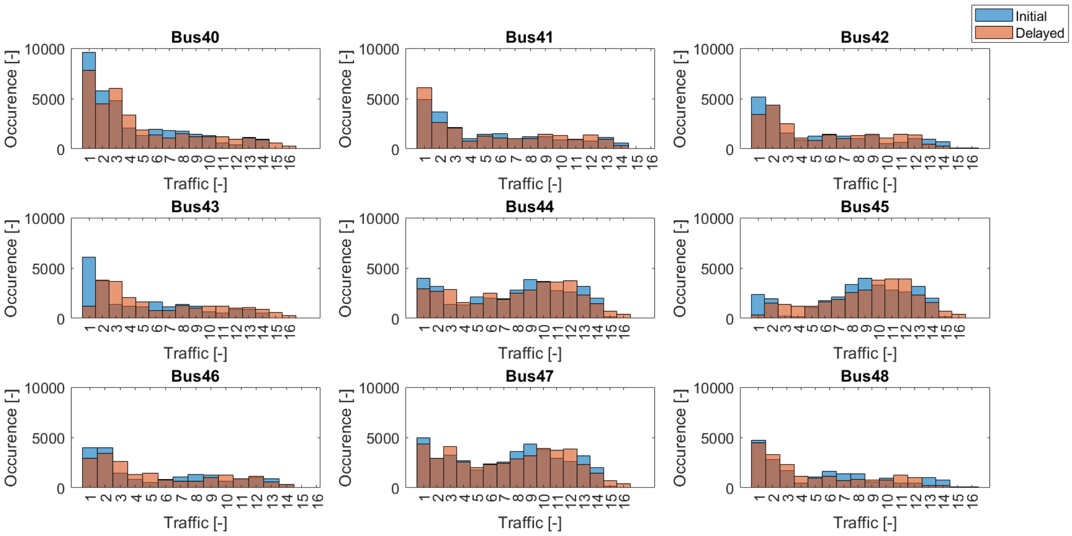
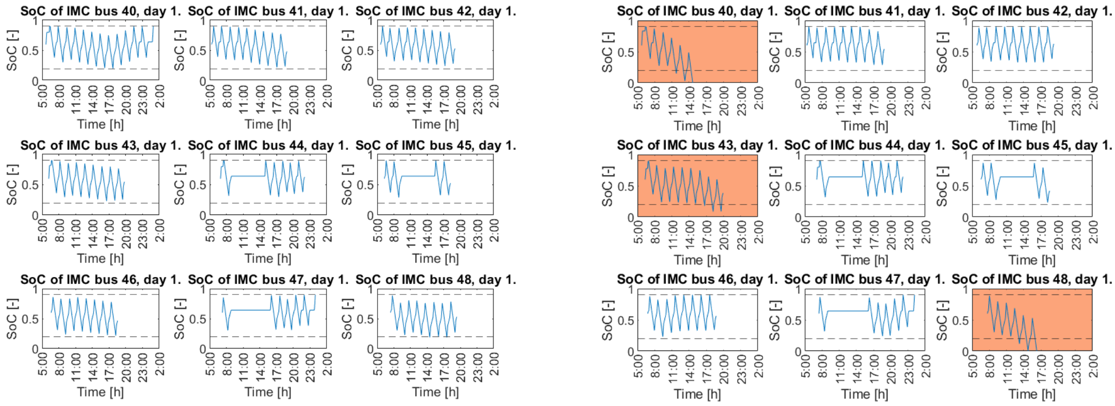
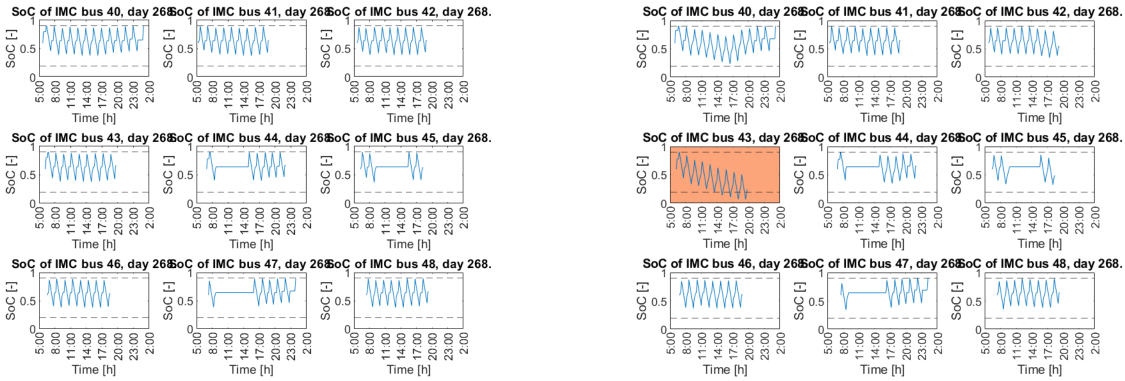


Figure 5.35: Traffic per IMC trolleybus. Comparison of initial data set and delayed traffic data set. Day 268



(a) Initial (b) Delayed Traffic

Figure 5.36: Comparison of SoC of IMC trolleybuses. (a) Initial data sets, (b) Delayed traffic data sets. Buses 44, 45 and 47 only operating in the morning and evening. Day 1



(a) Initial (b) Delayed Traffic

Figure 5.37: Comparison of SoC of IMC trolleybuses. (a) Initial data sets, (b) Delayed traffic data sets. Buses 44, 45 and 47 only operating in the morning and evening. Day 268

Important finding is that the charging scheme supported by estimator reacted to the change in traffic caused by delays and worked positively to keep the trolley-grid safety maintained. This is the major difference between the Valley-Charging approach and the conventional charging schemes which do not use any mechanism to react to such changes.

It also clearly emphasizes the importance of an opportunity charger. As the traffic is very stochastic system in reality, opportunity charger would provide confidence that the trolleybuses would have the chance to curtail their power demand significantly exactly in cases of traffic delays and then compensate for it at the opportunity charger. It can also be inevitable to invest in new infrastructure even when the estimator-supported Valley-Charging scheme is used. This would allow the IMC trolleybuses equipped with this scheme operate in the full range of charging powers 0-240 [kW] and still stay operable.

Results show the significance of traffic density for integration of trolleybus new line. We could see that even though the estimator reacted appropriately and curtailed the charging power demand, high traffic prevented some of the buses from finishing their service with sufficient SoC level. In terms of traffic, the trolley-grid seems to have certain traffic beyond which it would make it inoperable. Having said that, the importance to have as much time alone on a section as possible was clearly demonstrated. With increasing traffic in the form of either adding new public transport lines to the trolley-grid or of traffic jams, multiple vehicles on the line would either block the charging and make the vehicles low on energy or endanger the infrastructure by high charging powers.

5.3.2. EV Charger

To test the adaptability of the estimator to an increased demand on a section, an EV charger was placed at 600 [m] on section 24 which is the last section within the trolley-grid before exiting into battery mode. The power of the charger was set to be 100 [kW]. Like this, the power demand on section 24, and thus for substation 12, is constantly increased by 100 [kW] and corresponding transmission losses. It will be tested how the estimator can react to it. In reality, the IMC trolleybuses and their power demand would be the preferred load over the EV charger. In case of a voltage drop, the EV charger would be the one to step down and curtail its supply.

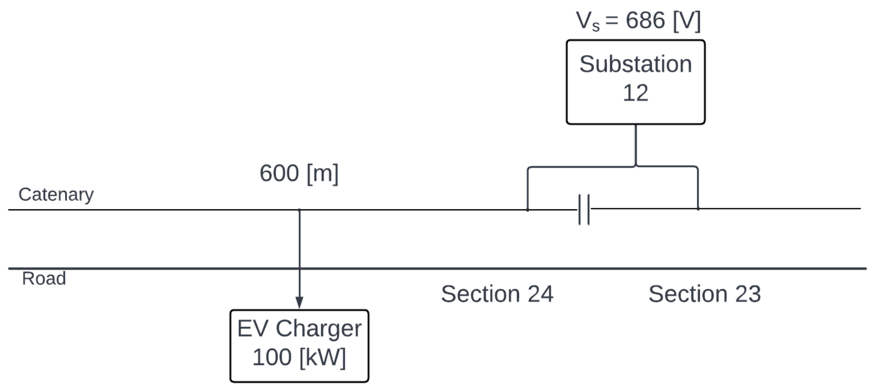
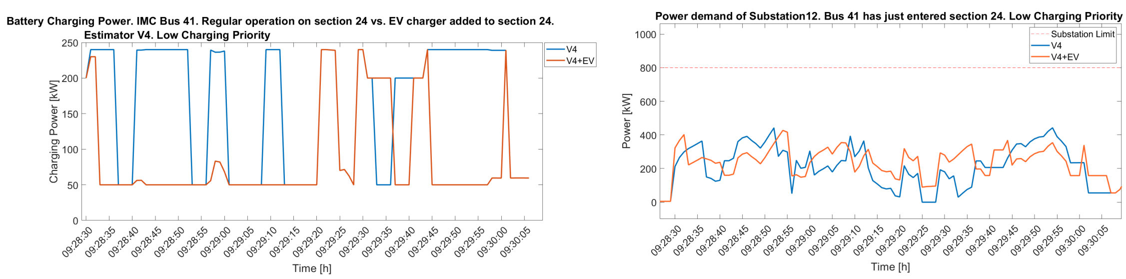


Figure 5.38: Placement of a 100 [kW] EV charger on section 24 800 [m] from substation.

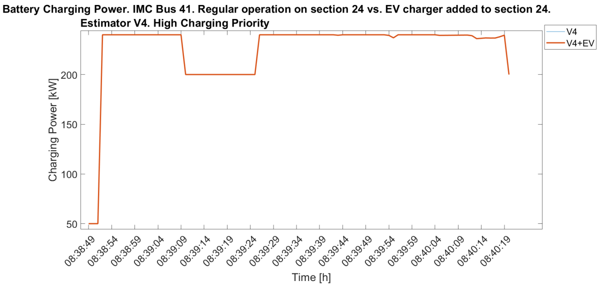
It is necessary to repeat that the latest version of the estimator is using the charging priority based on direction. This proved to be both effective and ineffective at the same time. Effective for cases when there are multiple vehicles on the same section which is the exact same benefit that was presented in 4.4.3. On the other hands, when the IMC vehicle has just entered the trolley-grid, which gives it low charging priority, the estimator senses the EV charger, or more precisely its power demand, and acts as if there was another vehicle resulting in charging power of just 50 [kW]. The charging priority counts with the other vehicles maximizing their charging power over time but the EV charger is not changing its load. The power capacity of the substation is left under-utilized in cases when there is only one vehicle going towards the Centraal station and EV charger. This phenomena is shown in figure 5.39. Even though the substation does not require any adjustment of the charging power, the estimator decides to do so.



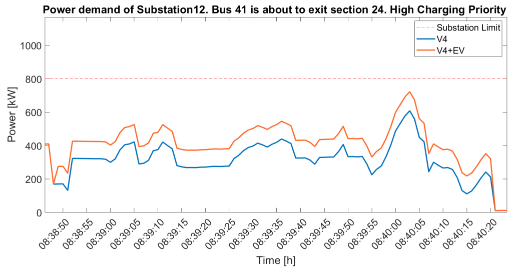
(a) Battery Charging Power (b) Power demand on substation 12

Figure 5.39: Effect of EV charger placed on section 24 on the behavior of the estimator. Battery Charging Power and power demand on substation 12 for bus 41 which has just entered the trolley-grid. Low charging priority. No EV charger vs. EV charger added

Following figure 5.40 shows the other direction of the route. It can be seen that an EV charger of just 100 [kW] does not represent a problem to the substation and the estimator suggests the same charging power to the bus which is about to leave the trolley-grid soon. Substation power demand is then just shifted by EV charging power and transmission losses.



(a) Battery Charging Power



(b) Power demand on substation 12

Figure 5.40: Effect of EV charger placed on section 24 on the behavior of the estimator. Battery Charging Power and power demand on substation 12 for bus 41 which is about to exit the trolley-grid. High charging priority. No EV charger vs. EV charger added

Table 5.5 shows the effect of the 100 [kW] EV charger on the energy collected per section. As expected, the trolleybuses were able to collect less energy on section 24 as there was the EV charger located. While other sections did not experience any significant change, section 38 increased its energy collected by more than 160 [kWh]. This is thanks to the conditional charging based on SoC. As the trolleybuses came to Arnhem Centraal with lower SoC level, the estimator ruled to charge longer and thus collected more energy there.

Table 5.5: Energy collected per section. Comparison of the effect of 100 [kW] EV charger placed on section 24 on the energy collected. Day 268

Charging Scheme	Energy Collected per Section [kWh]						Total
	24	23	2	3	37	38	
Valley-Charging	**752**	907	904	1059	635	451	4710
Valley-Charging + EV Charger	**570**	907	909	1061	635	613	4695

Another simulation setup with 300 [kW] charger can be seen in appendix D.

6

Conclusion & Discussion

Chapter 6 provides a summary of the findings of the thesis and draws conclusions. First section 6.1 focuses on the first research question and will thus reflect on the methods of available power capacity estimation. The second section 6.2 deals with the case study of the Arnhem trolley-grid. Last section 6.3 looks into recommendations for future research within this field.

6.1. Conclusion - Estimation Methods

The purpose of the first part of this thesis was to come up with methods to estimate the available power capacity for charging the battery of IMC trolleybuses by Valley-Charging approach. The objective of the task was to create a set of conditions and constraints that would determine the charging power which is high enough to ensure a sufficient amount of energy collected and not violate any technical limit of the trolley-grid at the same time.

One of the first steps is to estimate the traffic. For that, the concept of I_{σ} was proven to be beneficial to determine the traffic on the section (figure 4.57). Knowing the value of the current, which the IMC trolleybus would demand if it was connected alone to a section on an exact position and drawing the exact power, gives us insight into the circumstances on the section. By comparing the difference between the actual measured bus current I_{b} and I_{σ}, the presence of other vehicles on the same section can be sensed. If there is a significant difference, there is another vehicle as it affects the current going to the concerned IMC trolleybus. If the two values are equal ($\pm 0.5[A]$ to account for measurement error), the IMC trolleybus is alone on the section. It enables the estimator to determine whether the vehicle can demand high charging power (alone on section) or to curtail its charging power.

A relationship of trolleybus voltage and the available power capacity the substation can provide was found. By using real historical data, plots were made to see the data points form "cone" shapes with vertical line at the substation nominal voltage and hypotenuse representing the largest power capacity available for certain bus voltage (figure 3.4). Due to the large amount of data points within this region, a probabilistic analysis was made to form a relationship $P_{\mathrm{av}} = f(V_{\mathrm{b}}, \mathrm{K})$. For the probability level K, 95% was chosen as it is statistically acceptable value. The relationship says what the available substation power capacity P_{av} is in at least 95% cases for certain voltage V_{b} that is measured by the trolleybus. It provides sufficient insight into what the IMC trolleybus can demand based on its voltage.

With higher voltage, the density of data points is also higher and the probabilistic analysis to determine the available power is more accurate. An interesting phenomena can be seen around the substation nominal voltage where there are various power capacities possible ranging from lower hundreds up to the full potential of the substation. Having said that, it does not mean that if the bus measures nominal voltage, there is no pressure on the substation and the trolleybus can demand high power. That might be caused by either vehicles standing just very close to the substation and thus experiencing very little voltage drop even though there are other vehicles demanding power or by vehicles braking at the moment and providing power to other vehicles on the section. It was shown how conservative the relationship with its 95% probability is. Its use gave a lot of mismatch between the suggested value of power capacity and the actual power capacity (figures 4.58 and 5.28). A better study on the probability level that would provide both security and enough charging power is necessary.

The GPS location seems to be a crucial input of the estimator. It helps to determine the maximal power demand based on the position of the vehicle on the section so the limits of voltage, current and transmission losses are not broken. Power cap values were calculated for every position on the section (section 3.5). Two situations were assumed for the calculations; a single vehicle on a section and multiple vehicles on a section. When close to the feeder cable, it is the current preventing from drawing the whole potential power of the IMC trolleybus of 500 [kW] from the grid. It is mainly due to the overheating of the overhead lines. The further the vehicle gets from the substation the more it is limited by the transmission losses that should not go beyond 10% to keep the operation of the trolley-grid as economic as possible (figure 3.14). This is true for both of the assumed cases. Also, in any of them, the voltage is never the parameter preventing from full utilization of the IMC500 potential. Another finding is that the limitation of current is linear with the distance from substation, whereas the transmission losses are hyperbolic. The results clearly show that the further the vehicle is from the substation, the lower is the power it can demand without violating any limit.

6.2. Conclusion - Arnhem Case Study

The estimation methods were applied to integrate a new IMC trolleybus line with Valley-Charging approach to the Arnhem trolley-grid. Line 352 consisted of 9 IMC vehicles equipped by 130 [kWh] on-board batteries capable of maximal charging power of 240 [kW]. The IMC technology was employed for range extension. The trolleybuses would leave the trolley-grid and continue in autonomous mode for 28.8 [km] until they enter the trolley-grid on their way back. The purpose of the case study is to investigate how will the estimator-supported Valley-Charging help to integrate this new line into an already existing public transport network and to utilize the trolley-grid better by changing the charging power over time based on the conditions on the grid.

Four versions of the estimator decision trees were developed for simulating line 352 as accurately as possible. Each version was improved with a new measure/condition. First three of them were focused solely on all of the trolley-grid sections except for the Arnhem Centraal station, where the trolleybuses did not charge at all (chapter 4). Fourth version added a conditional charging based on the SoC of the trolleybuses on high traffic terminal station (chapter 5).

The decision tree of the first version (figure 4.43) started with determining the position of the vehicle. If it is in 50 [m] proximity from the switch between two sections, it is advised to charge low as the parameters in the following sections might be different and the estimator needs to take them into account first. The 50 [m] distance was determined based on average velocity and 3 [s]. Based on the I_σ concept, the estimator decides if the vehicles is the only one on a section or not. If yes, the power is limited by just power cap. If not, the bus voltage is used to determine the available power the trolleybus can demand based on historical data.

The first results showed that using the power cap values even for cases when multiple vehicles are present is not advisable. The behavior of other trolleybuses might affect the parameters of the section so much that a new approach of power cap values for multiple vehicles had to be added to the second version of estimator. Second set of results still experienced a lot of violations, especially in moments with high traffic. A charging priority based on the direction of the bus was then added. As trolleybus which has just entered the trolley-grid again from autonomous operation has a lot of charging time ahead, it can leave its charging potential for trolleybuses in the other direction which are about to leave the trolley-grid soon and need to maximize their energy yield.

By developing more complex and sophisticated versions of the estimator, the time when the technical limits of power, current and voltage were violated was cut down. In terms of current, it was a decrease of approx. 1800 and 180 in terms of the power. There were no violations of the voltage limit with the latest version of the estimator. It proves the claim that power and current are the most limiting factor whereas voltage is not.

The case study revealed that just adding a new trolleybus line might cause the power demand or current in the overhead lines go beyond the allowed limit (figures 4.15 & 4.17). Due to high traffic, only the traction power of the trolleybuses might be too high, especially when some of the trolleybuses are just accelerating. Operating 15 trolleybuses on the same route, as this thesis simulated, is coming close to the limit of the trolley-grid. Even though the research showed that there is enough power capacity to operate 15 vehicles, it requires more advanced charging scheme, such as the Valley-Charging to maximize the charging power when the conditions of the trolley-grid allow.

Previous research has shown that line 352 cannot be serviced by IMC trolleybuses with conventional charging methods nor even with adaptive charging without the necessity to invest into an opportunity charger. Thanks to the latest version of the estimator, line 352 was made operable with the Valley-Charging approach and was successfully integrated into the Arnhem trolley-grid. There was no need to build new infrastructure such as the opportunity charger. On average, the new IMC trolleybuses were able to collect up to 76 [kWh] of energy by charging per round-trip under the overhead lines, which is 4 [kWh] more than it is required to reliably cover the off-grid part of the route. If the Valley-Charging approach supported by estimator is compared to adaptive charging scheme, the buses were able to collect almost 1500 [kWh] less energy with adaptive charging on one day. In terms of limit violations, the Valley-Charging is comparable to 150/100 scheme while collecting 3400 [kWh] more energy. (tables 5.2 & 5.3). By using the Valley-Charging approach, 10 [min] of opportunity charging time of each IMC trolleybus was saved compared to adaptive charging, not mentioning the investment costs (table 5.4). The Valley-Charging supported by the estimator does not need the opportunity charger while adaptive scheme would require the investment.

Most of the violations occurred on sections 2 and 3 which are both fed by substation 1. There were both breaches of power and current limits. Both sections are more than kilometer long with feeder cable placed near the section switch. Because of that, the sections are prone to high traffic. This does not have to mean high traffic on just one section. Unlike the current limit, the power limit depends on the traffic from both sections that are fed by one substation. However, the estimator only works with quantities measured on-board and GPS location, thus can only predict the behavior on one section and not the other. The estimator suggests the charging power based on the traffic on one section only. It could be seen that 70% of the 120% power limit fails with latest version of the estimator happened because of this phenomena (figure 4.45), which technically is not a mistake of the estimator. These undesired mistakes could be solved by installing one substation per section. The estimator would only work with power limit of that one section and the estimation methods would be much more accurate in terms of the power limit.

Also, the estimation methods always fail when multiple vehicles are connected on the same section and they are located on opposite sides from the feed-in point of the substation. Their power demands affect each others voltage and current measurements just by the voltage drop at the feeder cable connection point. It is desirable to construct sections suitable for the estimation of the state of the trolley-grid to maximize the length of one side of the section from the feed-in point.

Even though the Valley-Charging approach helped to integrate line 352, there still were limit violations which some of them might be harmful to the trolley-grid infrastructure. The reason is that the case study ran rather extreme traffic scenario. The municipality of Arnhem are planning to extend the trolley-grid by approx. 800 [m], which means there will be more time for the IMC trolleybuses to pick-up enough energy. In the future, the plan is to extend it by 2.5 - 3.5 [km] in total, which would allow the estimator to act more conservative and prevent the trolleybuses from violating the limits.

The charging priority based on the direction proved to be very effective in reducing the power demand on substation in cases of high traffic. However, this measure was sometimes too strict. Charging priority might decrease the charging power unreasonably. Even though 100 [kW] decrease would be enough to meet the power limit of the substation at the time, it goes from 240 [kW] to 50 [kW] instead, resulting in 90 [kW] of wasted charging potential. The magnitude of charging power decrease to 50

[kW] was set like this as 50 [kW] is considered a safe value to increase the charging power by. A way of quantifying the curtailment of the charging power better, for example based on a voltage drop and substation voltage, might be necessary when dealing with other loads.

6.3. Recommendations and Future Work

The field of In-Motion Charging (IMC) technology for trolleybuses is still emerging and offers a lot of directions to focus the research on. Municipalities are either operating first IMC lines or just studying pilot projects.

The results clearly suggest that determining the number of vehicles on the section more precisely could be a way to make the estimation methods more accurate. So far, the estimation methods presented in this thesis could tell whether the vehicles is alone on the section or not. The number of vehicles could be used to predict the total power demand that can occur in the worst case and would help to quantify the curtailment of charging power. One way to achieve it is to study the voltage drop. Taking into account the position of the vehicle and the value of V_σ (voltage the trolleybus would measure on that position drawing that amount of power when alone on the section), the estimator could try to tell what power demand from other vehicles could cause the difference between V_σ and bus voltage V_b.

One of the estimation methods presented was the relationship of $P_\mathrm{av} = f(V_\mathrm{b}, \mathrm{K})$. An extension of the relationship by position of the trolleybus would help to make the probability level K more accurate. If the voltage drop would be found too high for this position, the level should be increased to make the possible available power lower.

The public transport system is very unpredictable, stochastic and data-oriented. To understand the relationship between the data sets, such as how is the curve of minimal voltage on the section related to the power demand of the trolleybuses connected and their position, a machine-learning approach could be applied. It could give deeper understanding of the data and also change conditions for the estimation methods over time the further it goes with the set of data it has studied.

In reality, the trolleybuses make use of several mechanisms that try to prevent the trolley-grid from failures. As an example, when the trolleybus measures too low voltage, it puts limit on the traction power, signals the driver who slows down and knows the trolleybus should not accelerate during this period of time. The model used for simulation in this Master thesis only used the curtailment of the charging power as a feature of the Valley-Charging approach for IMC vehicles, but the traction power curtailment is not implemented in the model. By adding it, the simulations could get closer to the real-life operation and the trolleybuses would gain more flexibility.

Another aspect that could be studied and that would help to electrify fossil-fuel lines and integrate them to the trolley-grid is concept called economic driving. It is a set of rules the drivers should obey in order to relieve the stress put on the substation. One of the rules is that the drivers should not accelerate when they are approaching a bus stops but slowly coast there instead. Creating new data sets that would take this drivers' behavior into account and running the simulation would show how big of a difference can this concept make as it would reduce the amount of power demand peaks.

If we think about the IMC technology in a conventional way, the energy from the battery should only be used when outside of the grid. One great benefit of the Valley-Charging approach with estimator could be that the trolleybus might be advised to stop drawing power from the overhead lines and go into the battery-mode while within the trolley-grid when unpleasant circumstances such as too low voltage occur. Just like this, the IMC trolleybus could help the substation to recover from the voltage drop and make space for regular trolleybuses to draw traction power. The biggest challenge is to conveniently determine the threshold when the trolleybus should switch to the battery-mode. If chosen too low, it might be too late to prevent any kind of damage, and if chosen too high, the charging potential would be unreasonably decreased.

The results have also shown that the current might be a limiting factor in utilizing the trolley-grid maximally. However, there is very little information on what the actual current limitation of the overhead lines is. There should be a peak value that would instantly damage the overhead lines or any devices connected and there also should be a duration for which the high current would have long-term effects. One approach to study the current is how it contributes to over-heating of the overhead lines. The estimator knows what the current of the trolleybus is and could thus predict how severe the current value is in terms of heating the cables. This could enable the estimator to regulate the charging power from not only power perspective but also from current perspective.

The literature can provide relevant information on the infrastructure for IMC systems, such as the segmentation of the overhead lines. Very few researches focus on the vehicles itself, meaning an innovative charging approach or even a battery technology that should be used on-board. The choice of suitable battery technology depends heavily on the segmentation of the overhead lines. The more segmented, the higher the amount of charging cycles. This case differs from cases when there are only two segments, under the overhead lines and off-grid, for the whole duration of the one-way trip, where there will only be one cycle.

A

Estimator Version 1 (V1) Simulation Results

A.1. Day 117

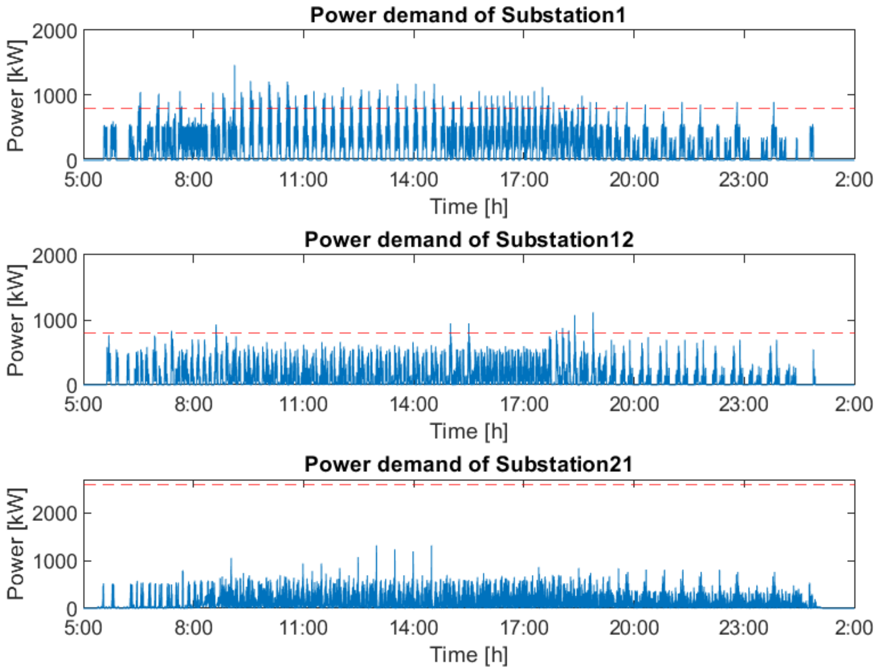


Figure A.1: Substation power demand during **day 117**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 scenario.

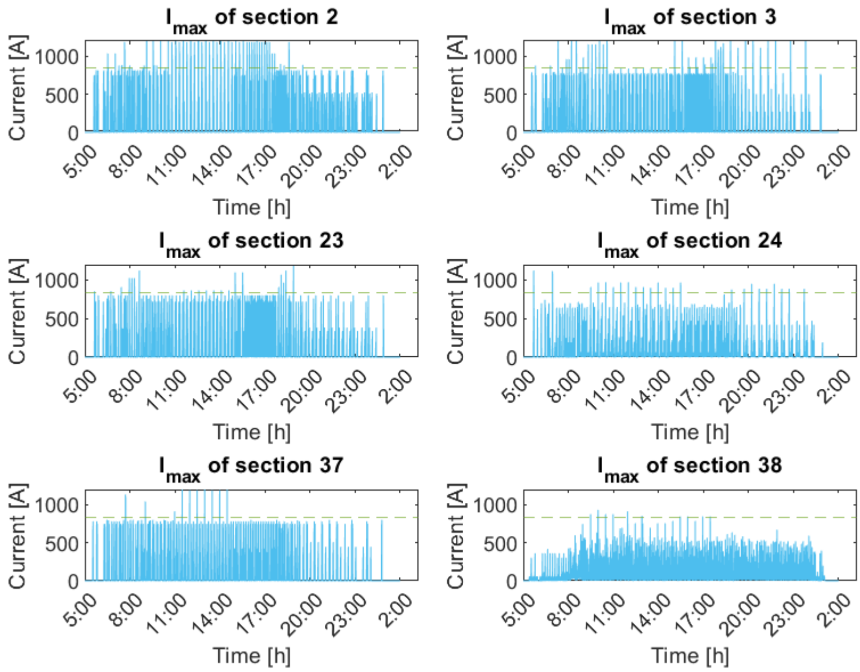


Figure A.2: Maximal current on each section of line 352 route during **day 117**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V1 scenario.

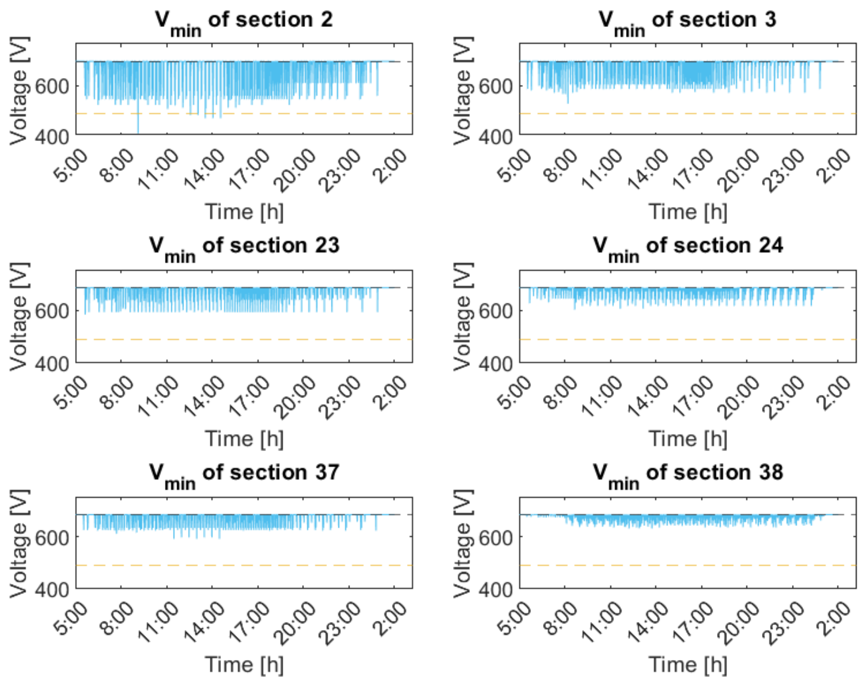


Figure A.3: Minimal section voltage for each section of line 352 during **day 117**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

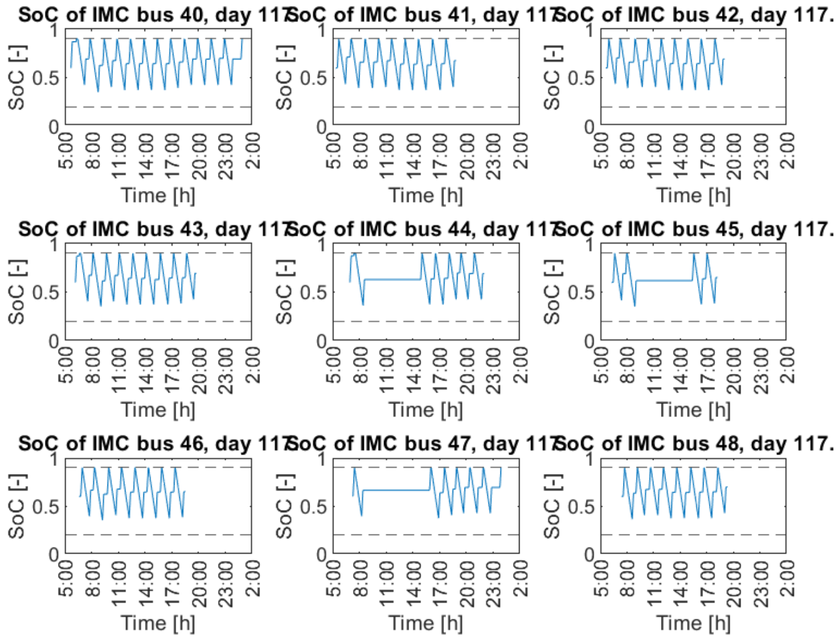


Figure A.4: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 117**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

A.2. Day 197

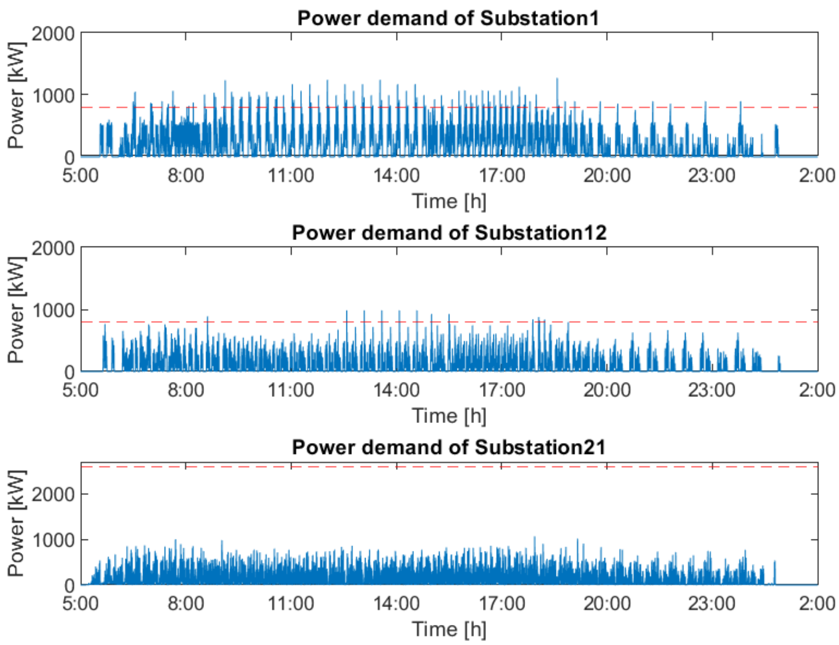


Figure A.5: Substation power demand during **day 197**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 scenario.

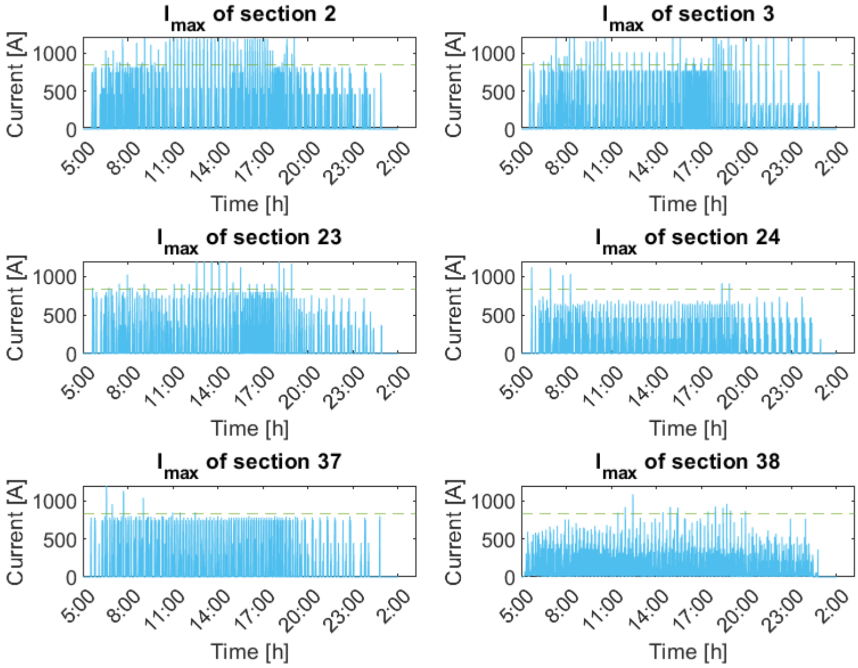


Figure A.6: Maximal current on each section of line 352 route during **day 197**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V1 scenario.

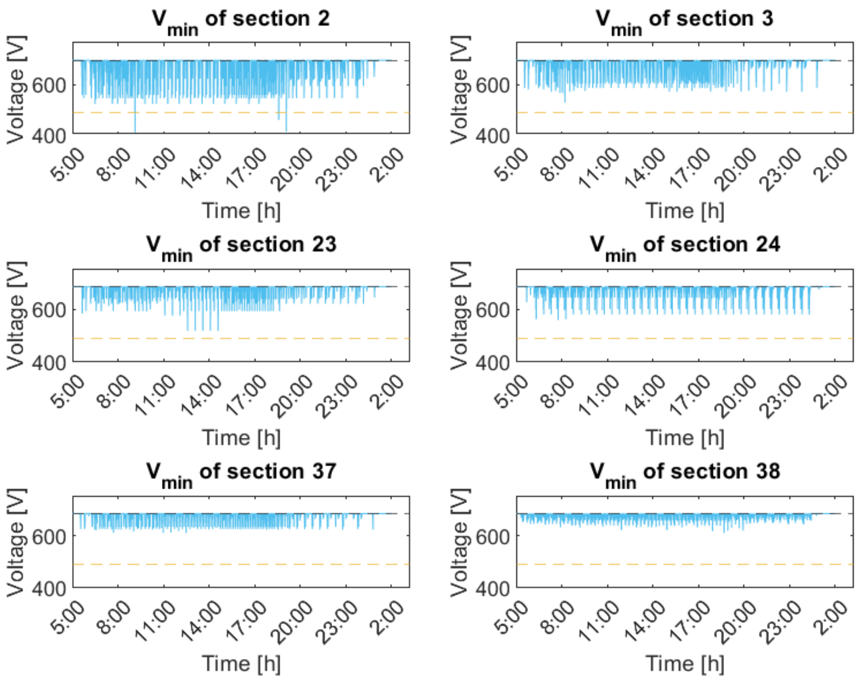


Figure A.7: Minimal section voltage for each section of line 352 during **day 197**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

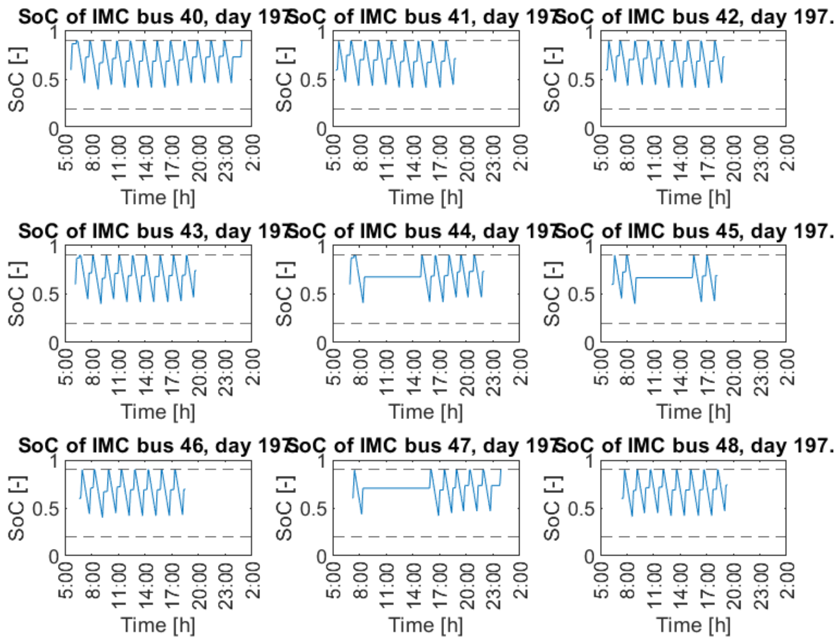


Figure A.8: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 197**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

A.3. Day 200

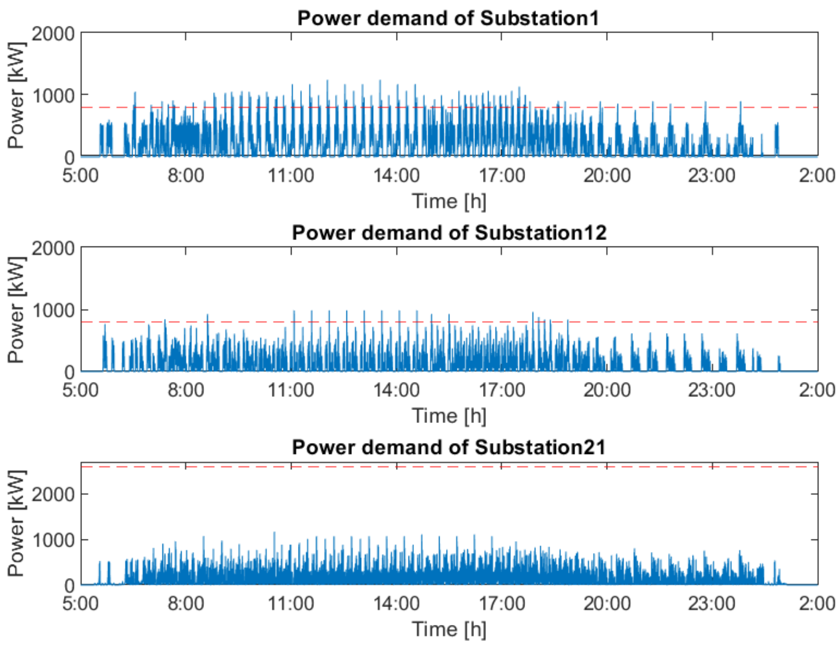


Figure A.9: Substation power demand during **day 200**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 scenario.

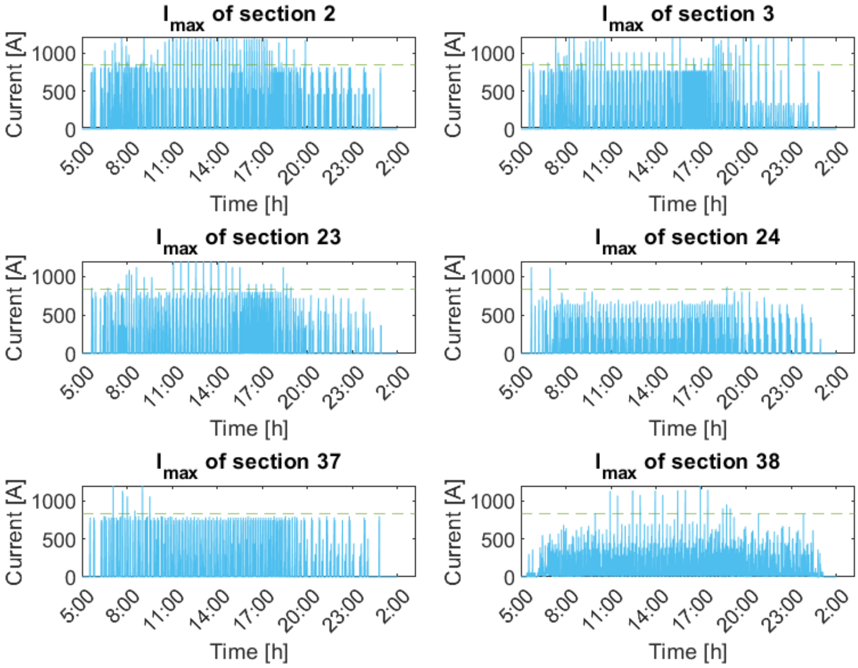


Figure A.10: Maximal current on each section of line 352 route during **day 200**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V1 scenario.

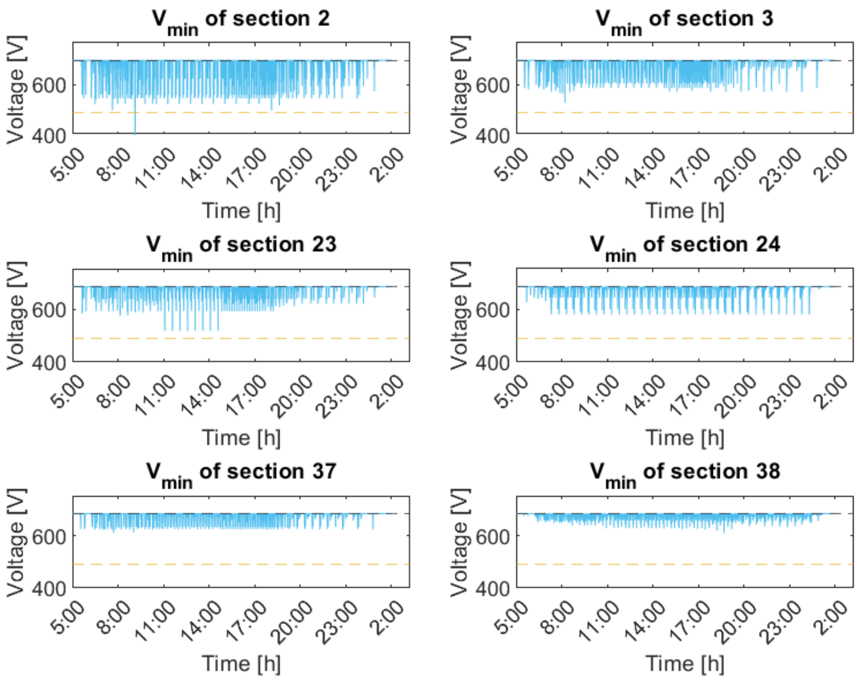


Figure A.11: Minimal section voltage for each section of line 352 during **day 200**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

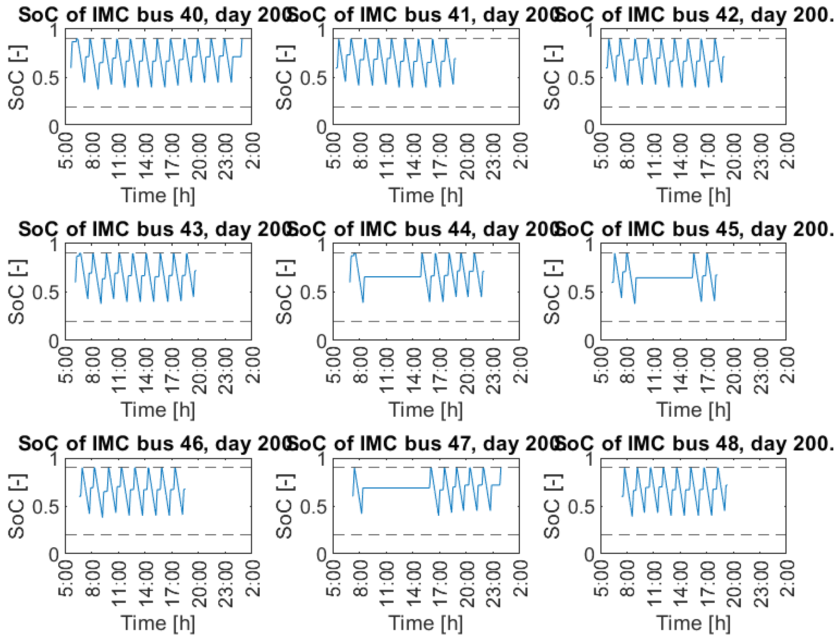


Figure A.12: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 200**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

A.4. Day 268

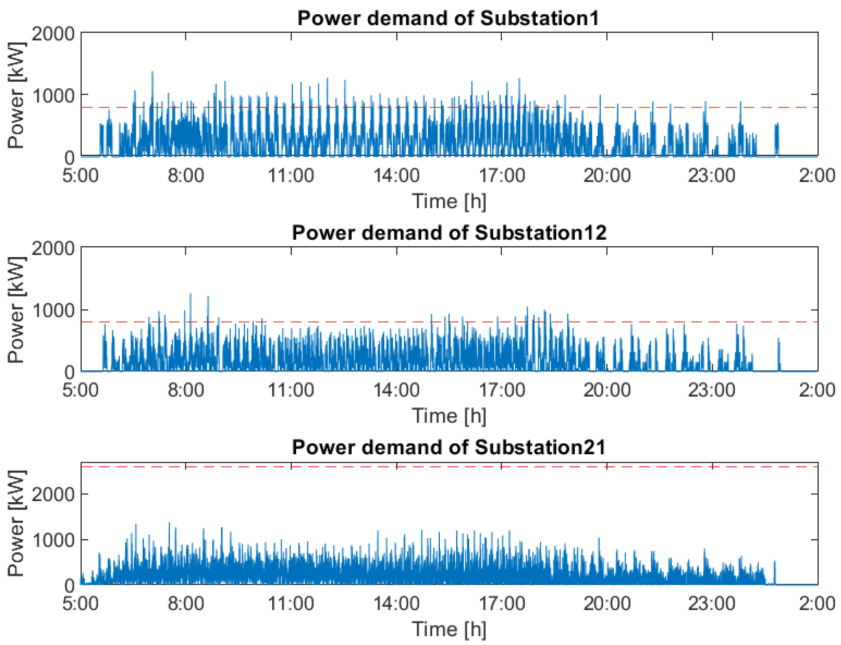


Figure A.13: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 scenario.

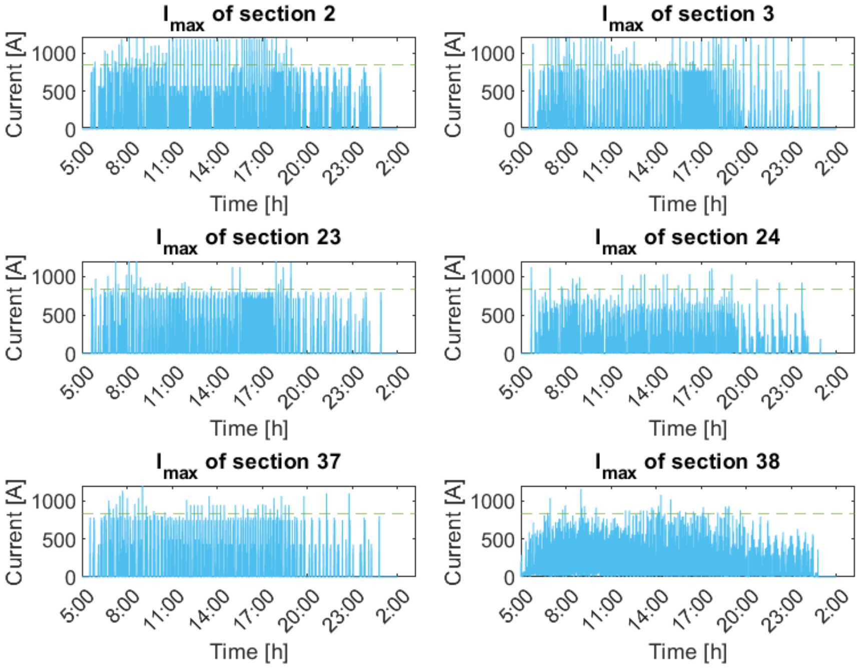


Figure A.14: Maximal current on each section of line 352 route during **day 268**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V1 scenario.

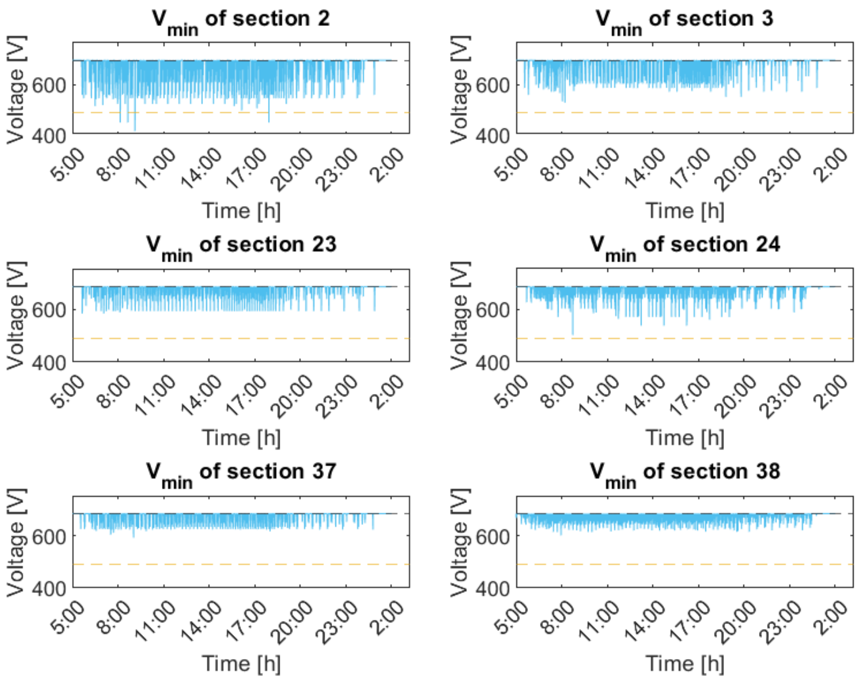


Figure A.15: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

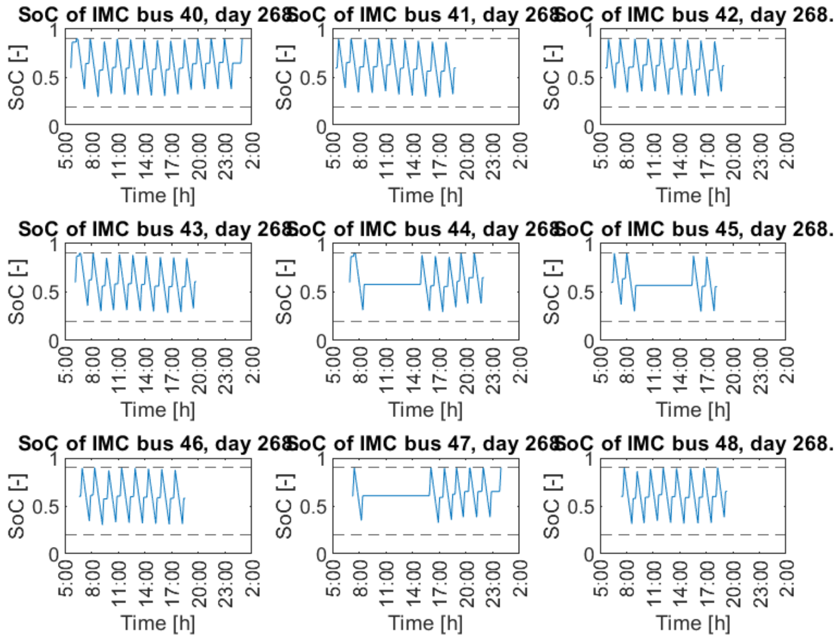


Figure A.16: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 268**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

A.5. Day 305

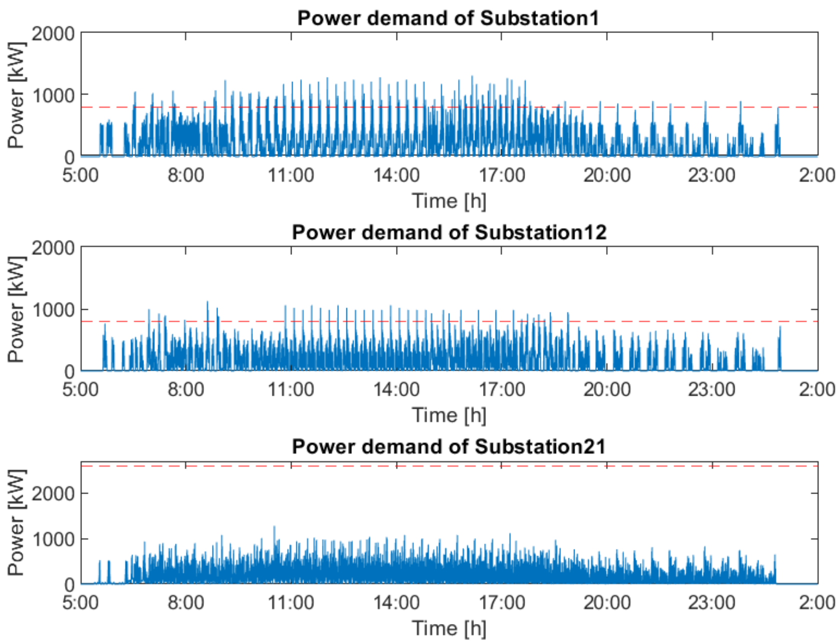


Figure A.17: Substation power demand during **day 305**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V1 scenario.

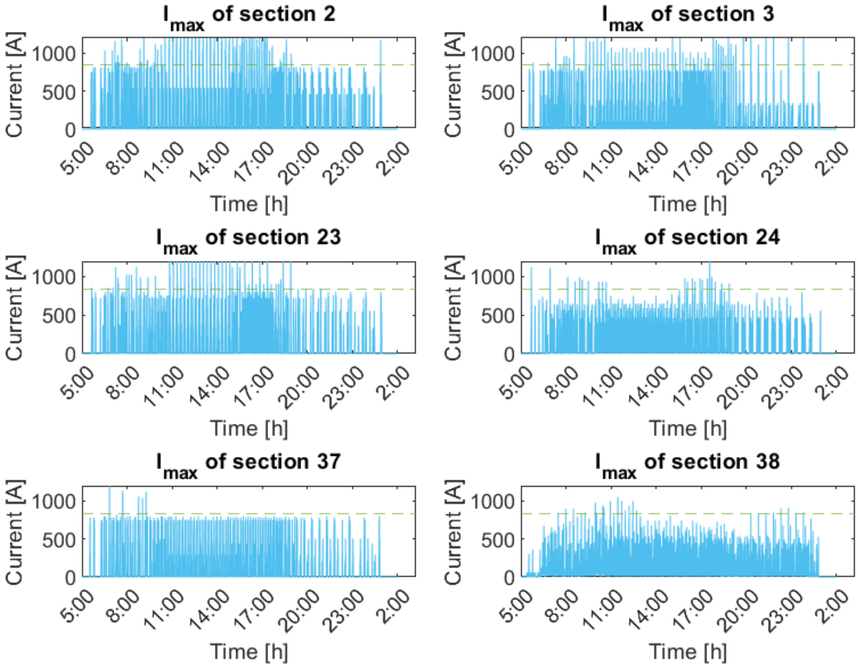


Figure A.18: Maximal current on each section of line 352 route during **day 305**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V1 scenario.

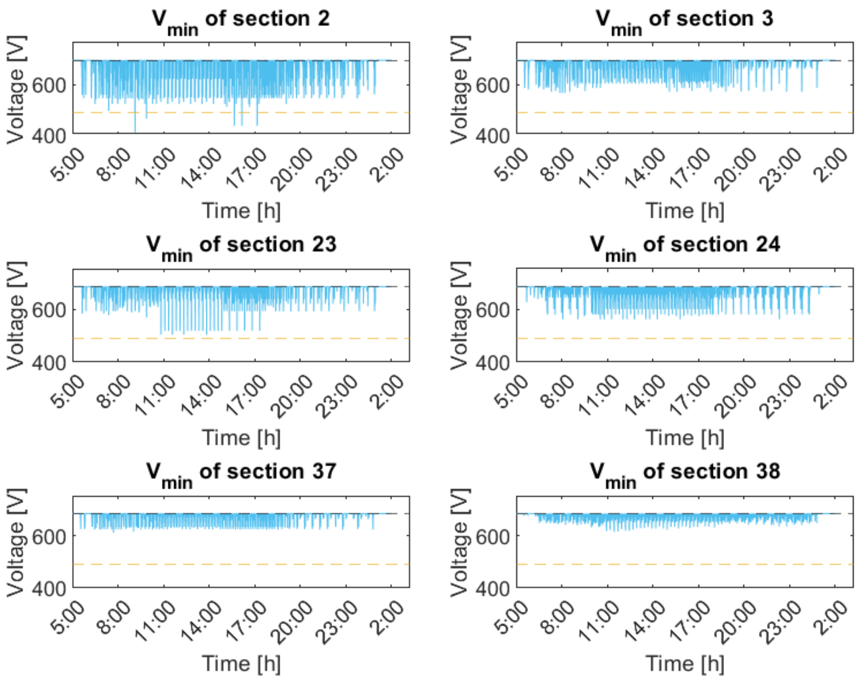


Figure A.19: Minimal section voltage for each section of line 352 during **day 305**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V1 scenario.

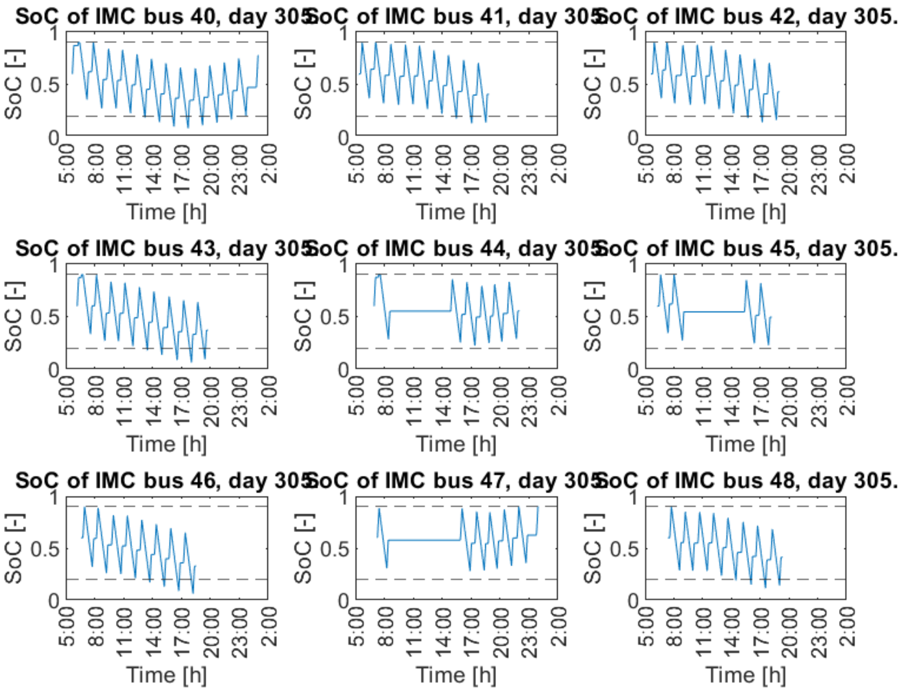


Figure A.20: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 305**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V1 scenario.

B

Estimator Version 2 (V2) Simulation Results

B.1. Day 117

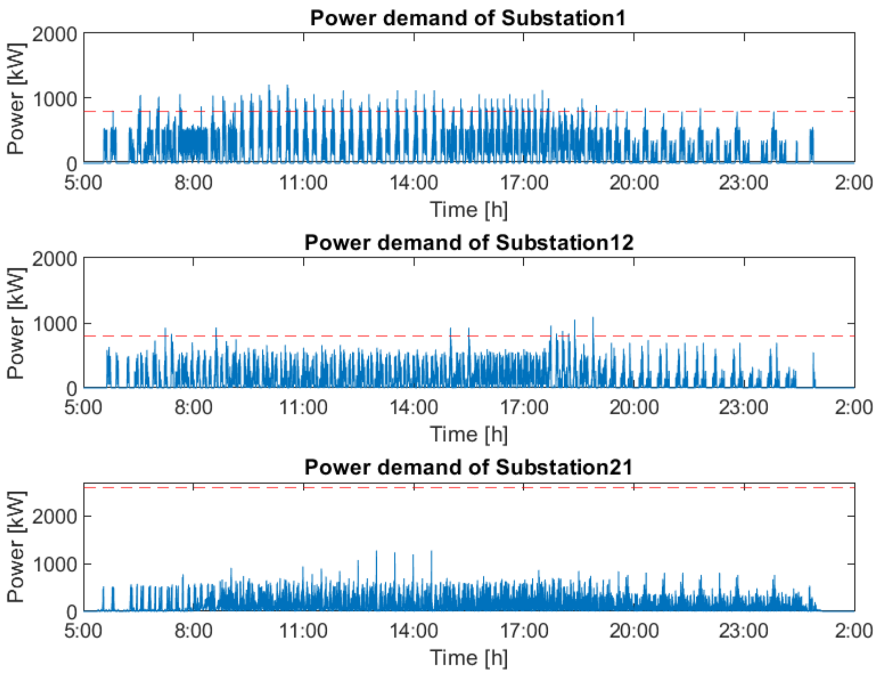


Figure B.1: Substation power demand during **day 117**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 scenario.

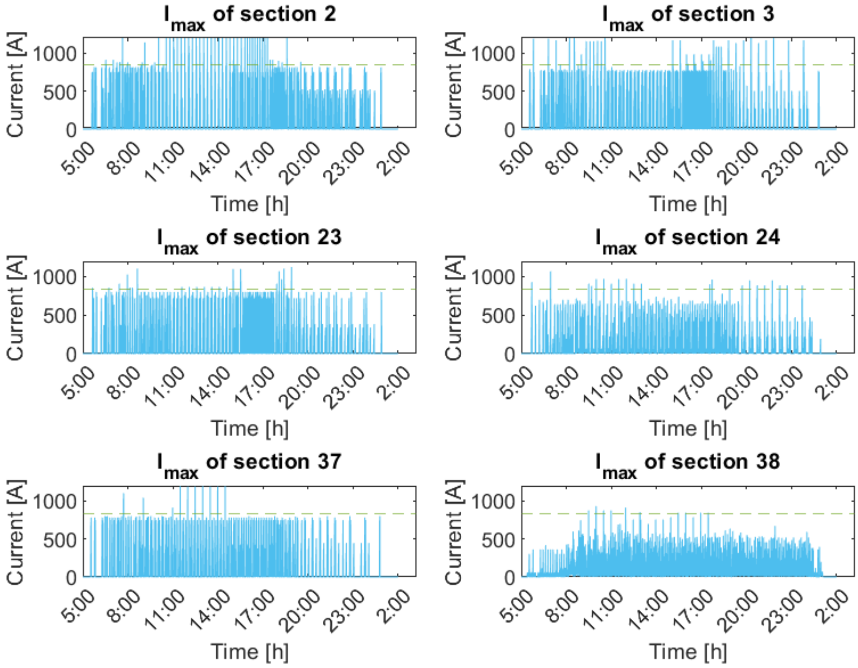


Figure B.2: Maximal current on each section of line 352 route during **day 117**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V2 scenario.

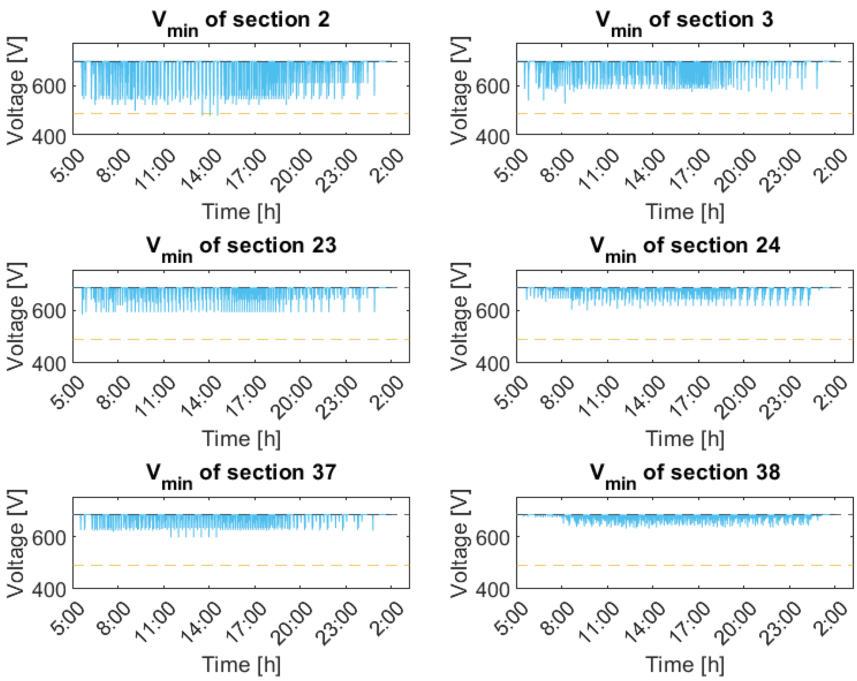


Figure B.3: Minimal section voltage for each section of line 352 during **day 117**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

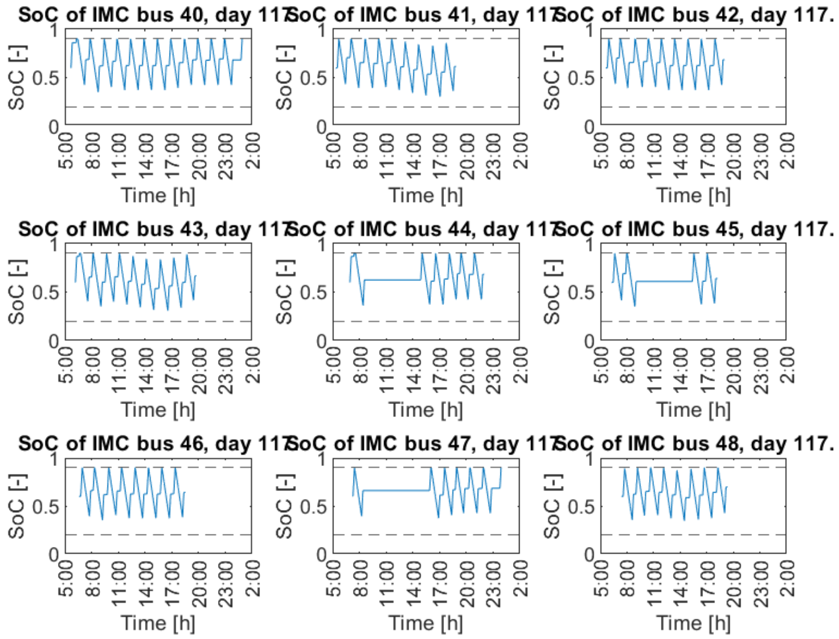


Figure B.4: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 117**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

B.2. Day 197

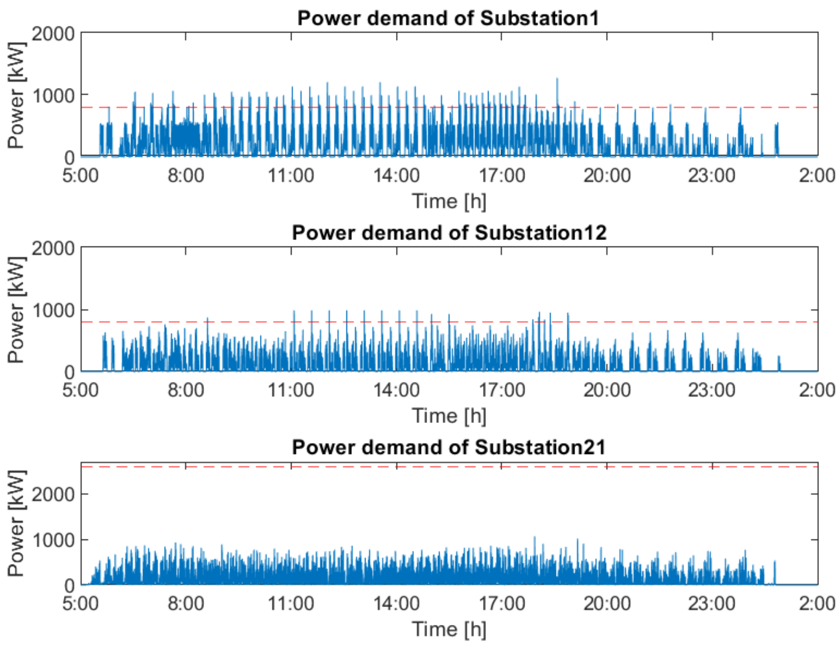


Figure B.5: Substation power demand during **day 197**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 scenario.

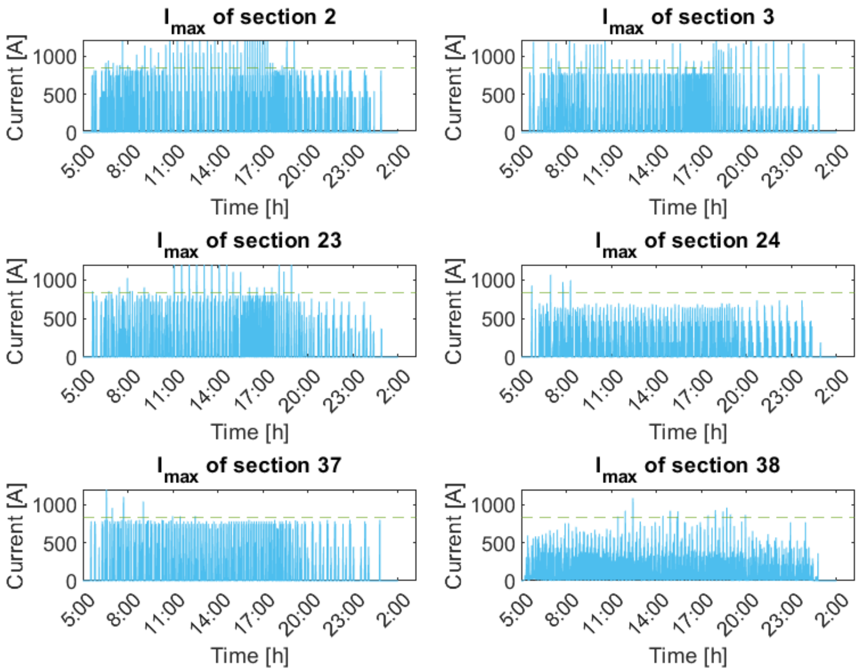


Figure B.6: Maximal current on each section of line 352 route during **day 197**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V2 scenario.

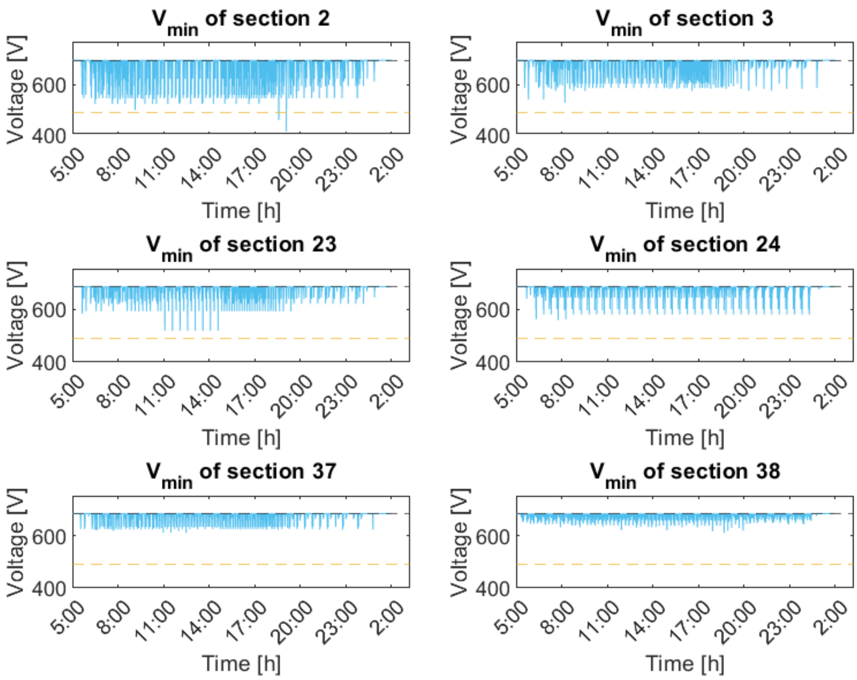


Figure B.7: Minimal section voltage for each section of line 352 during **day 197**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

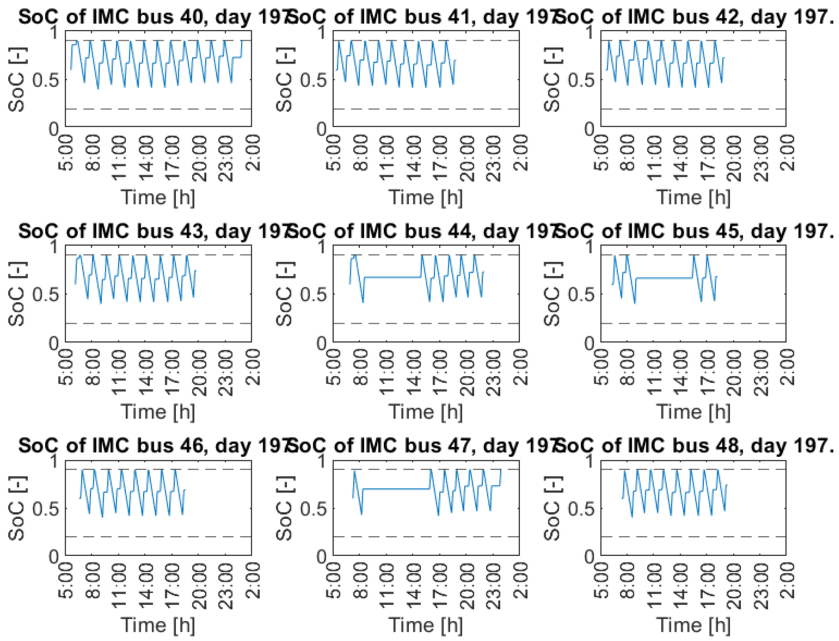


Figure B.8: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 197**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

B.3. Day 200

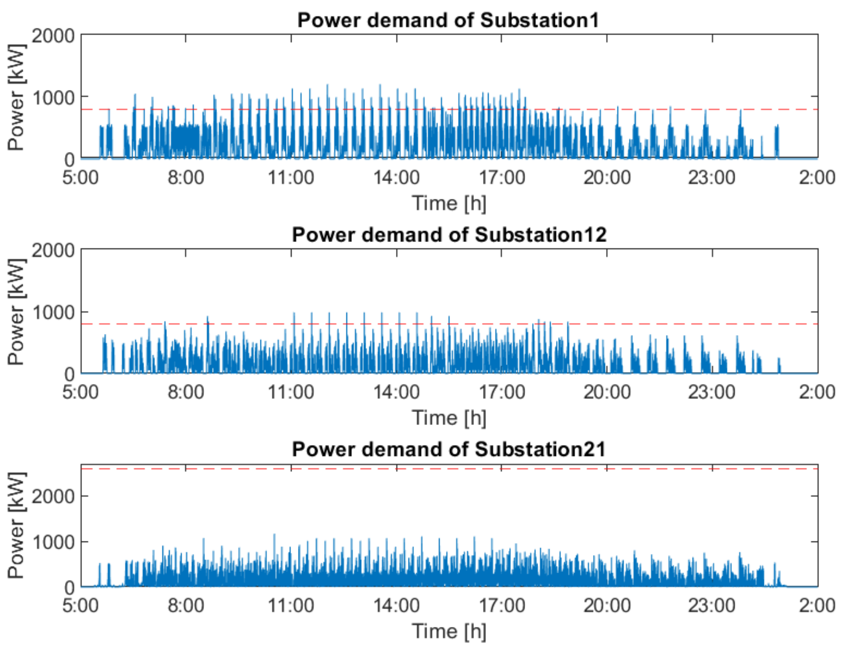


Figure B.9: Substation power demand during **day 200**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 scenario.

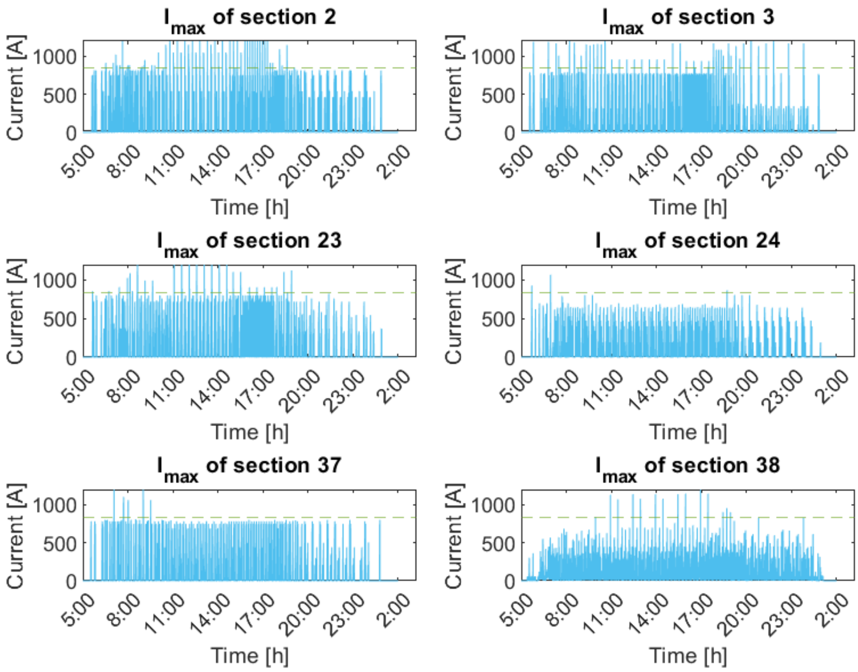


Figure B.10: Maximal current on each section of line 352 route during **day 200**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V2 scenario.

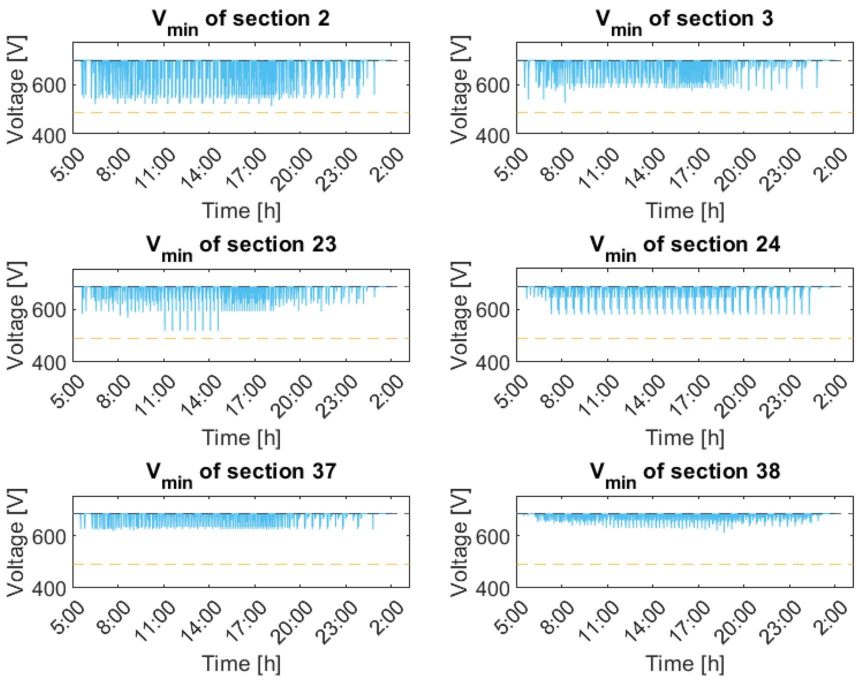


Figure B.11: Minimal section voltage for each section of line 352 during **day 200**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

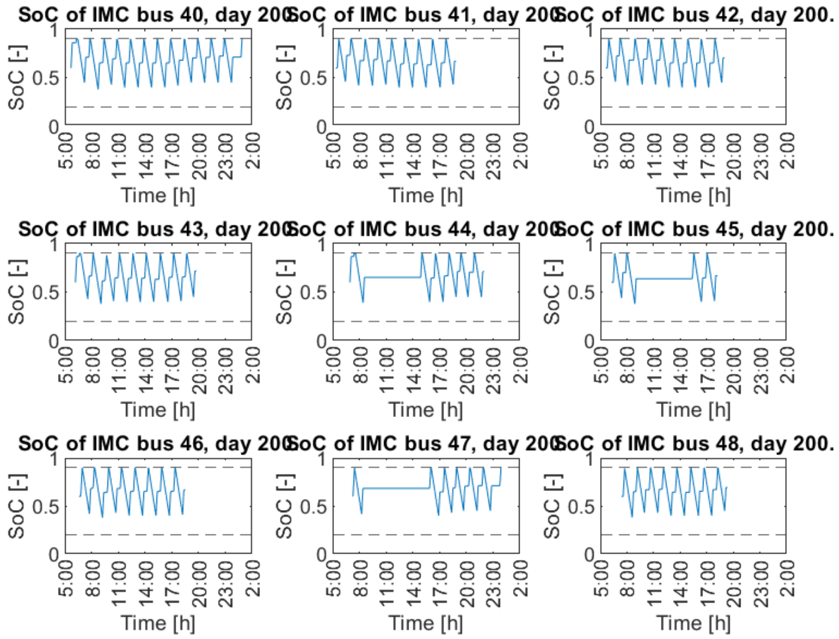


Figure B.12: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 200**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

B.4. Day 268

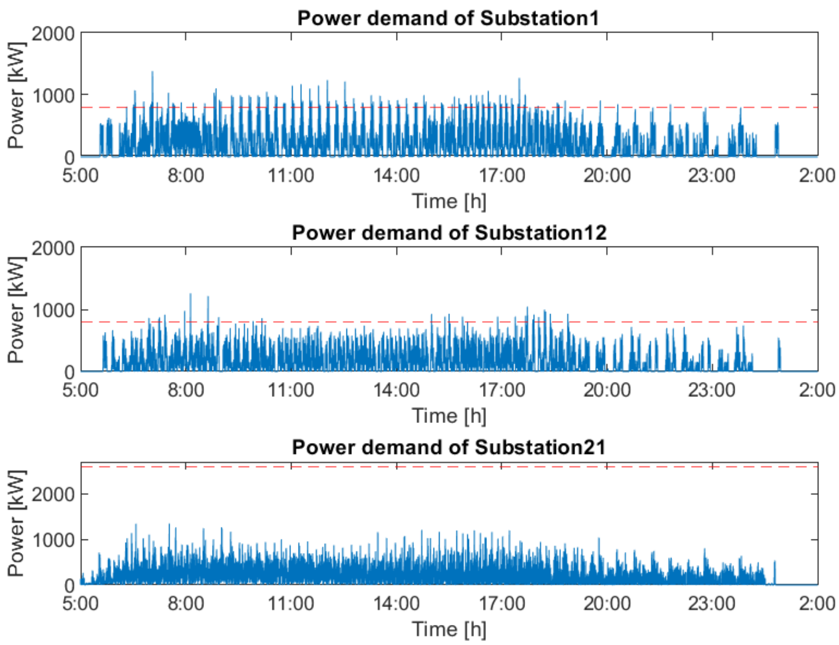


Figure B.13: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 scenario.

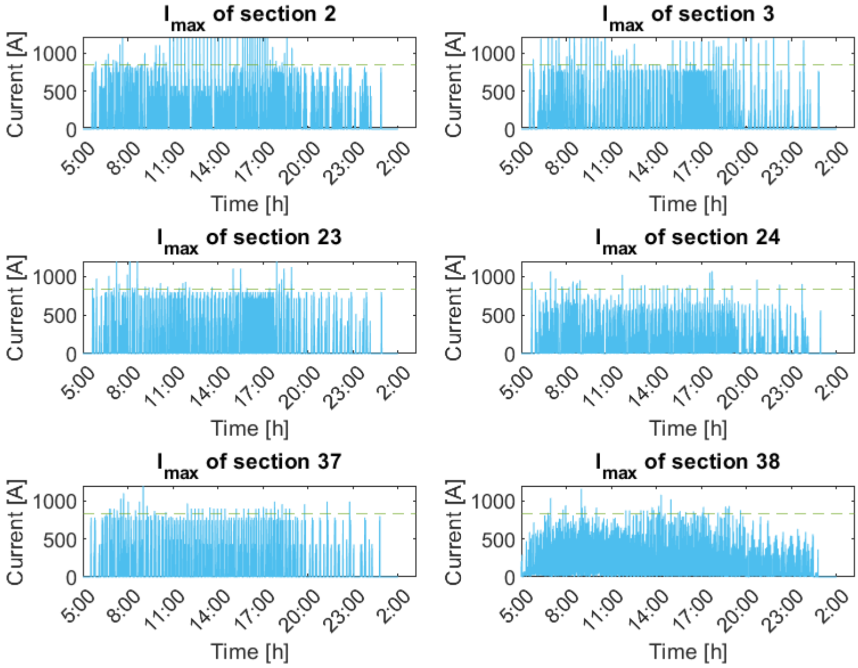


Figure B.14: Maximal current on each section of line 352 route during **day 268**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V2 scenario.

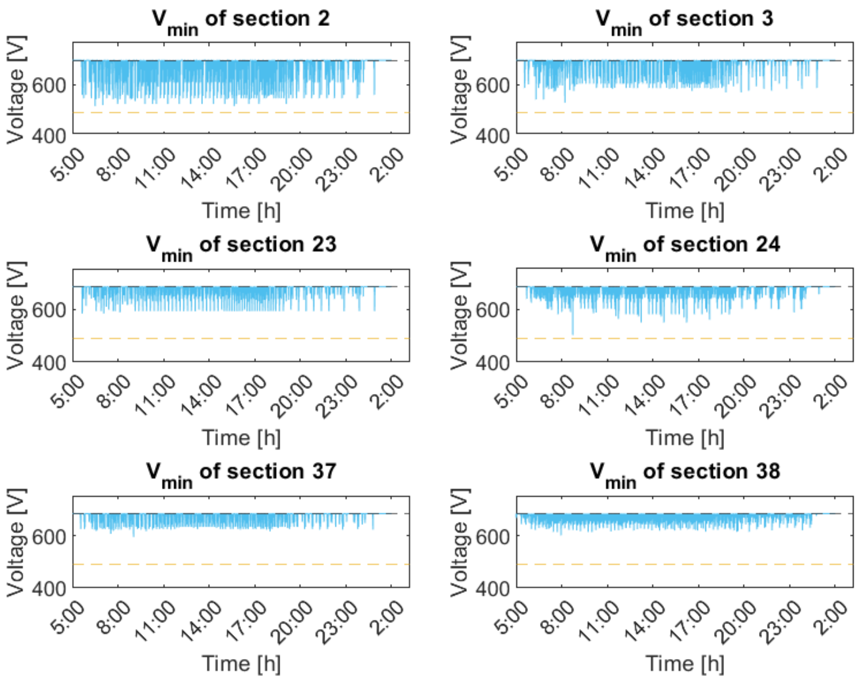


Figure B.15: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

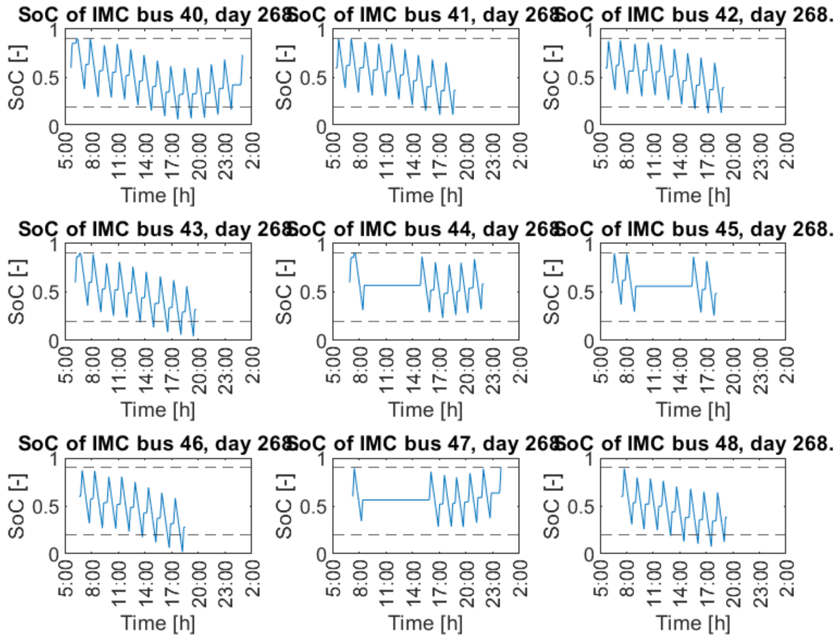


Figure B.16: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 268**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

B.5. Day 305

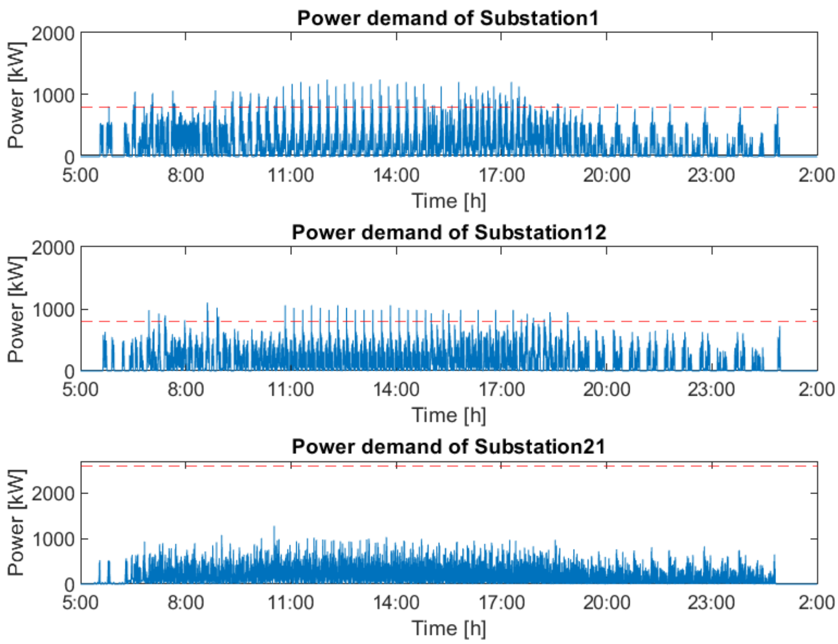


Figure B.17: Substation power demand during **day 305**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V2 scenario.

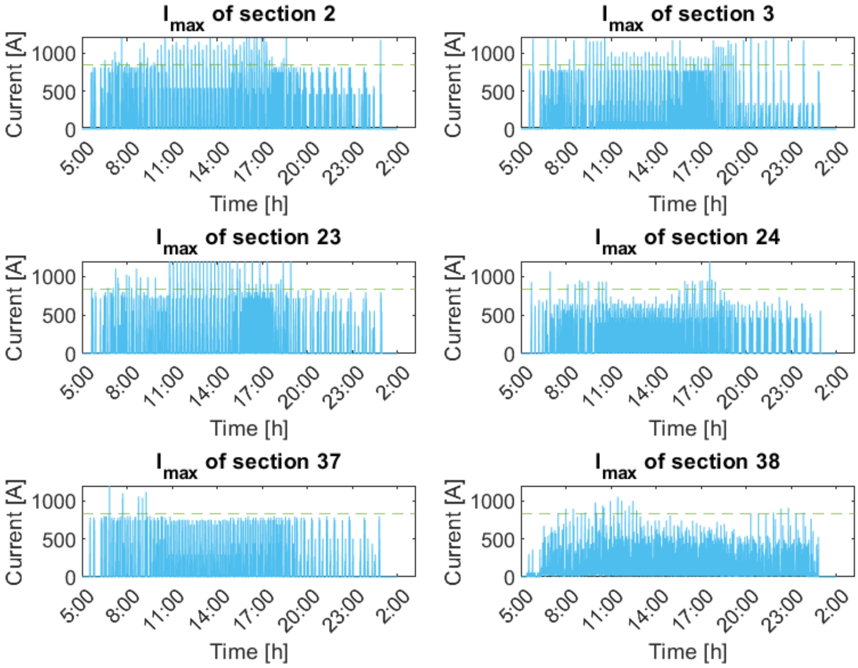


Figure B.18: Maximal current on each section of line 352 route during **day 305**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V2 scenario.

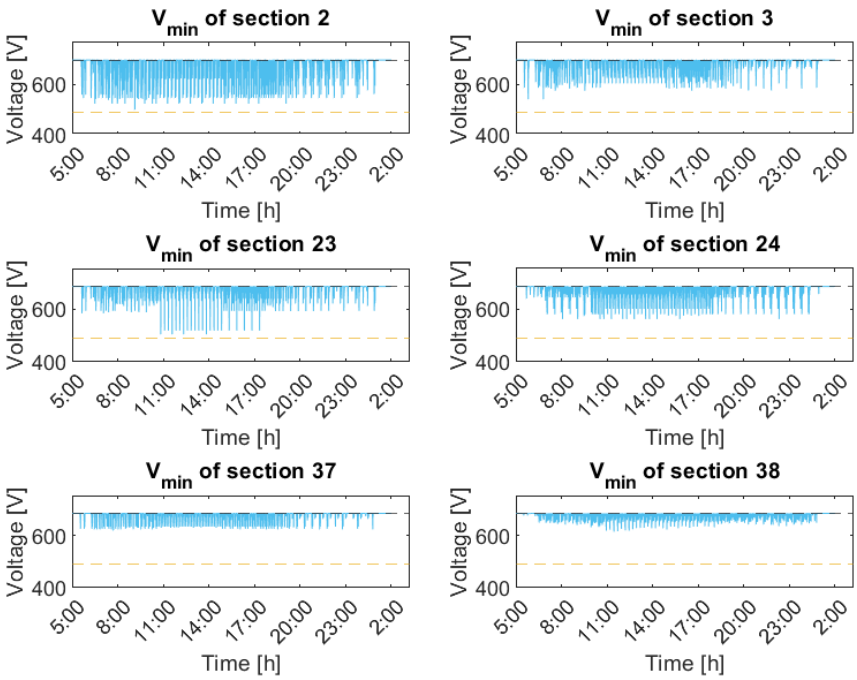


Figure B.19: Minimal section voltage for each section of line 352 during **day 305**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V2 scenario.

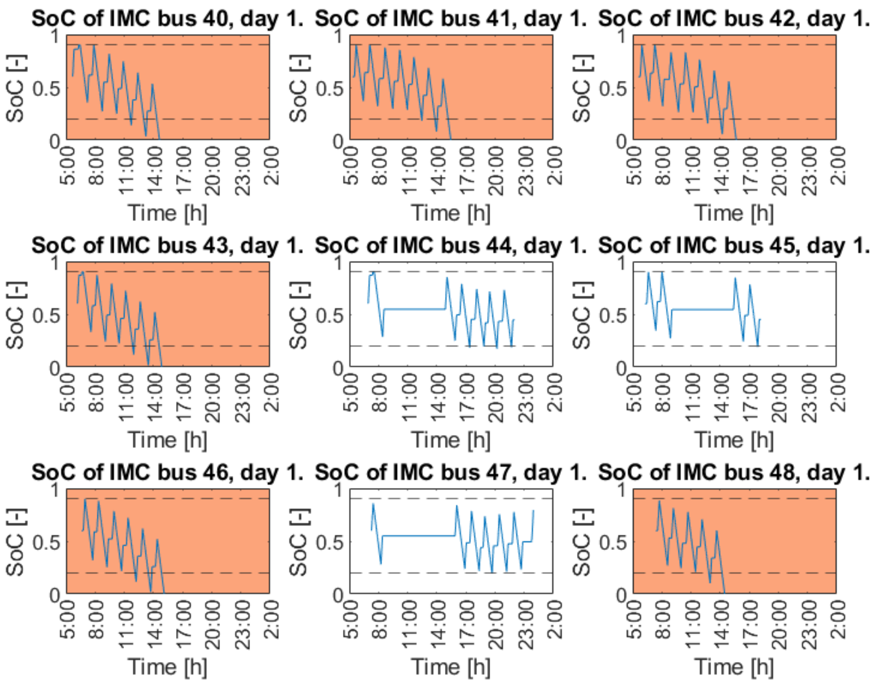


Figure B.20: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 305**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V2 scenario.

C

Estimator Version 3 (V3) Simulation Results

C.1. Day 117

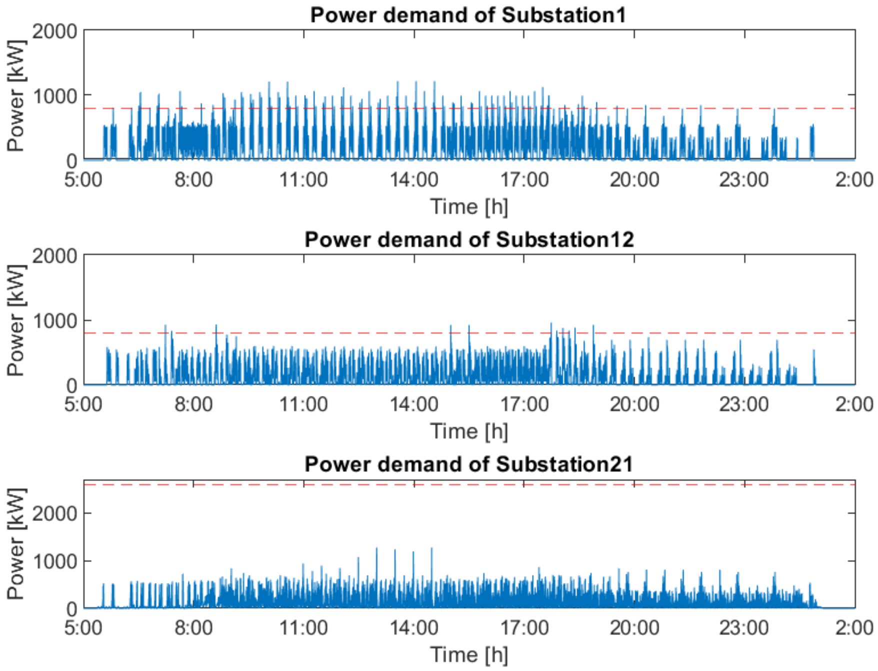


Figure C.1: Substation power demand during **day 117**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 scenario.

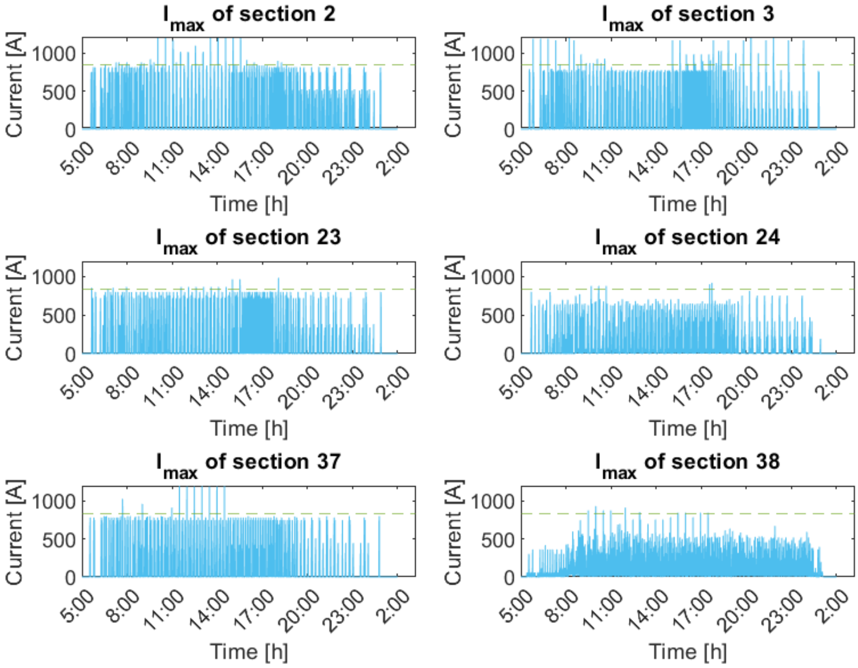


Figure C.2: Maximal current on each section of line 352 route during **day 117**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V3 scenario.

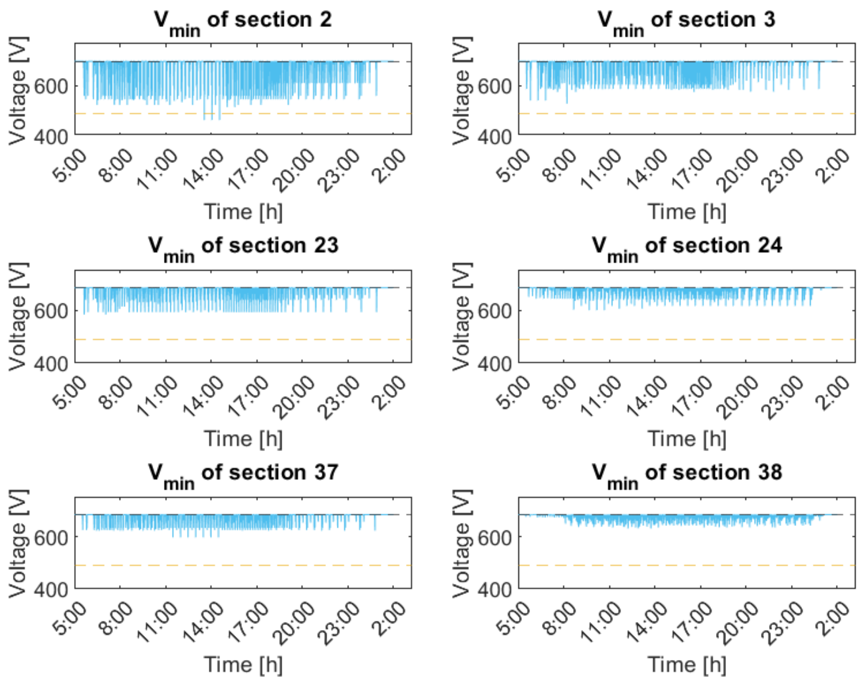


Figure C.3: Minimal section voltage for each section of line 352 during **day 117**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

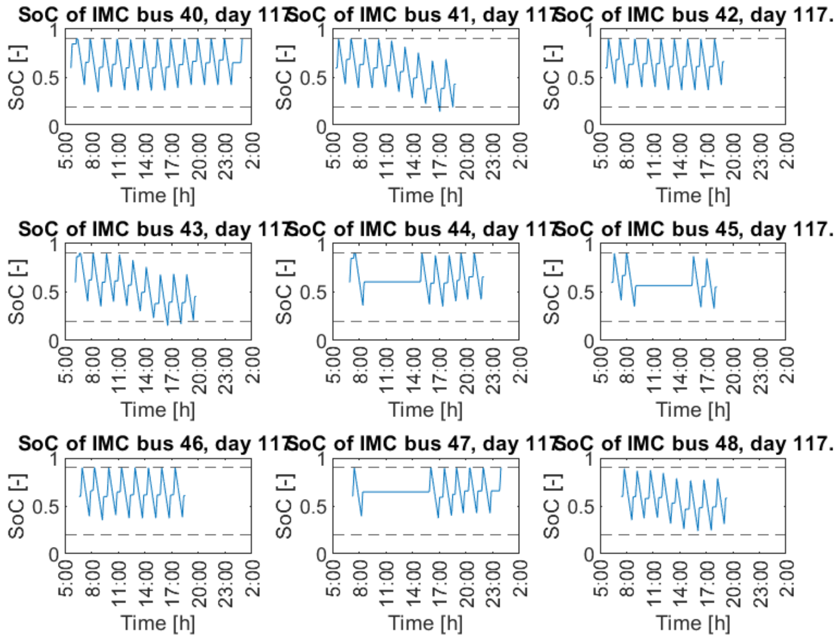


Figure C.4: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 117**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

C.2. Day 197

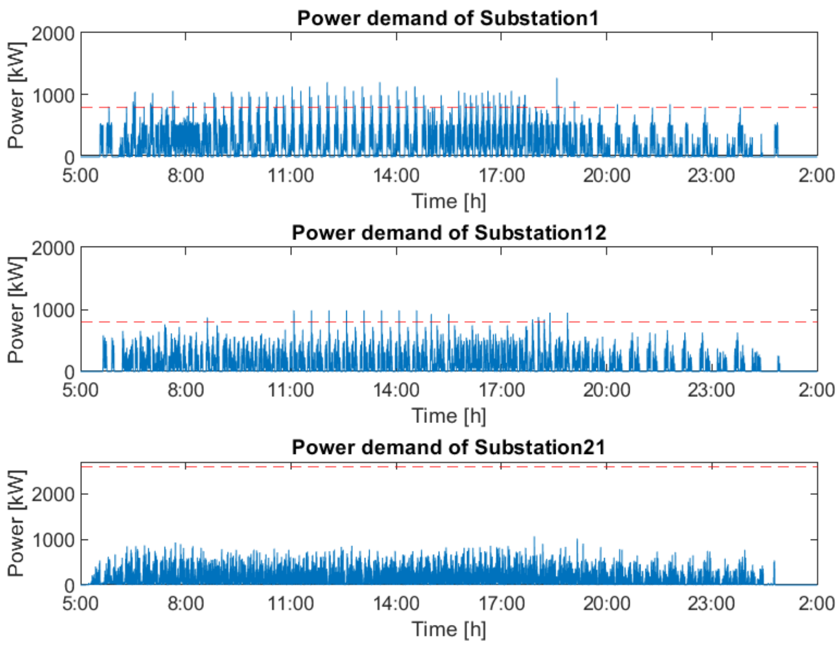


Figure C.5: Substation power demand during **day 197**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 scenario.

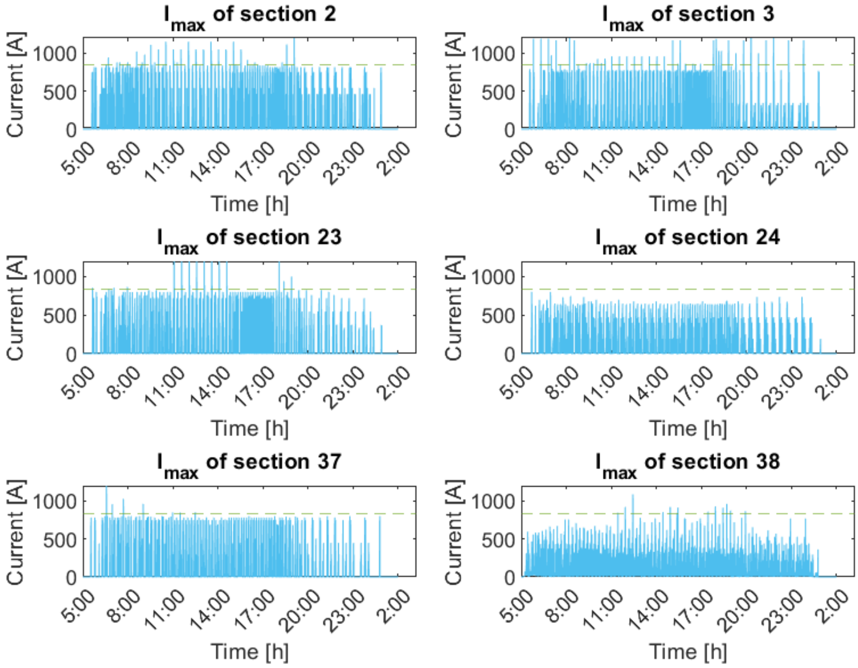


Figure C.6: Maximal current on each section of line 352 route during **day 197**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V3 scenario.

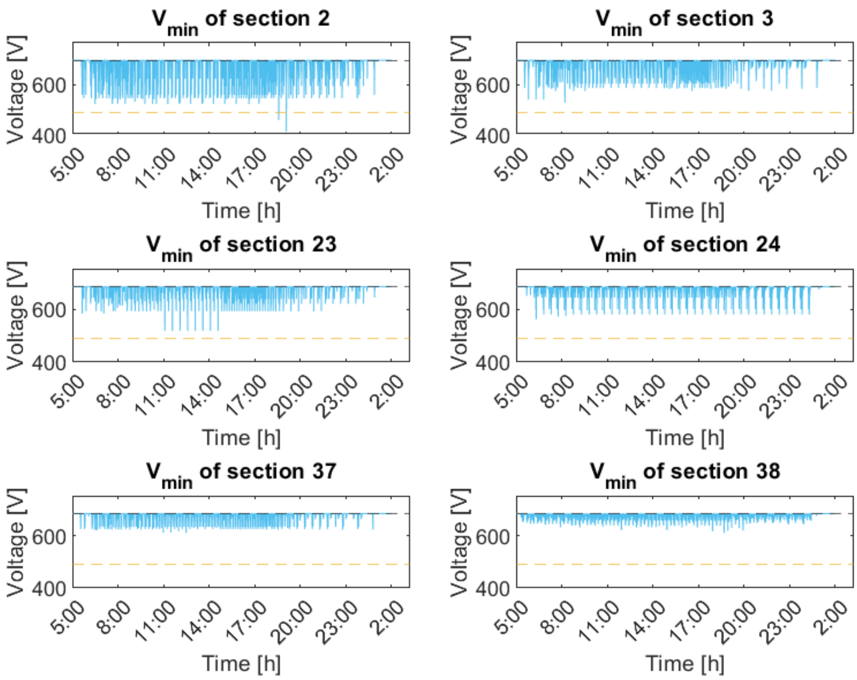


Figure C.7: Minimal section voltage for each section of line 352 during **day 197**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

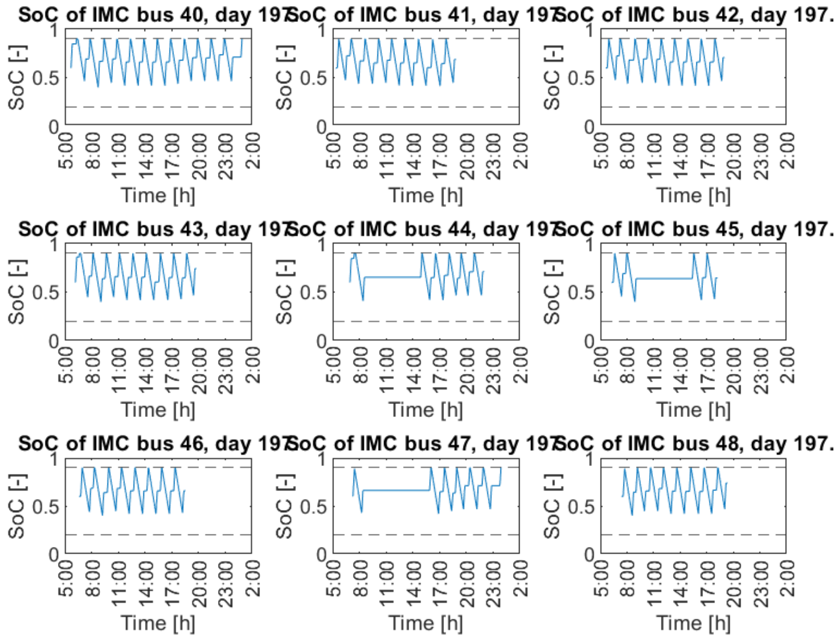


Figure C.8: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 197**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

C.3. Day 200

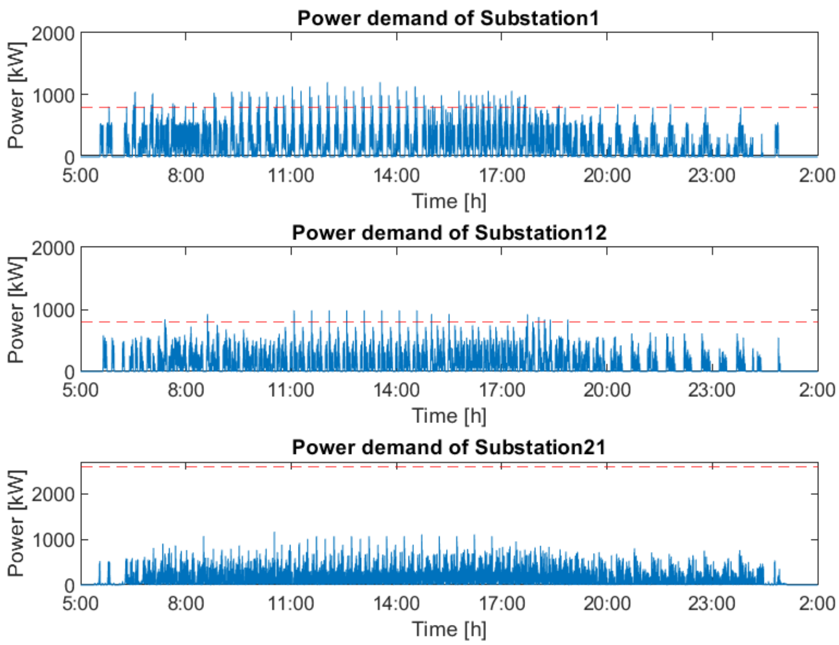


Figure C.9: Substation power demand during **day 200**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 scenario.

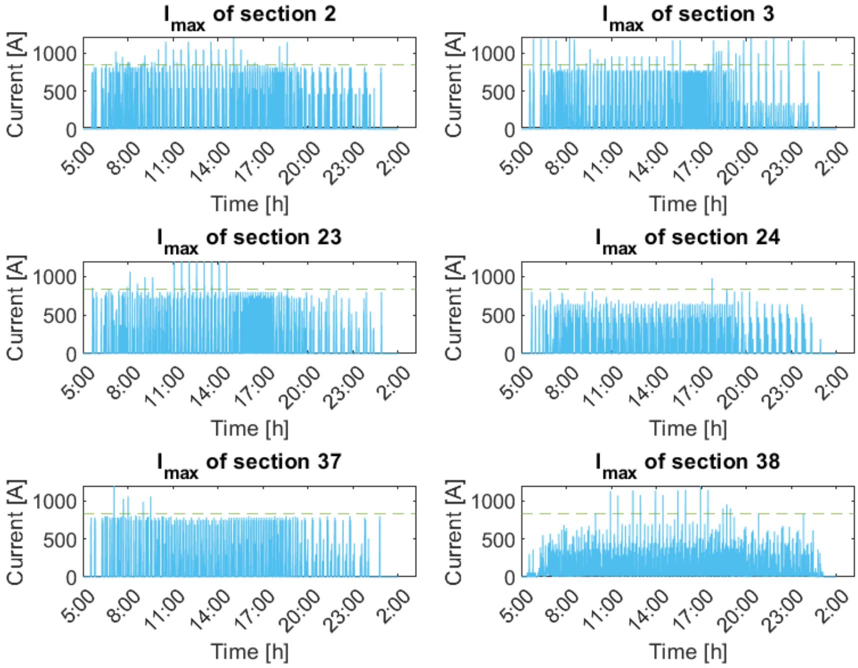


Figure C.10: Maximal current on each section of line 352 route during **day 200**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V3 scenario.

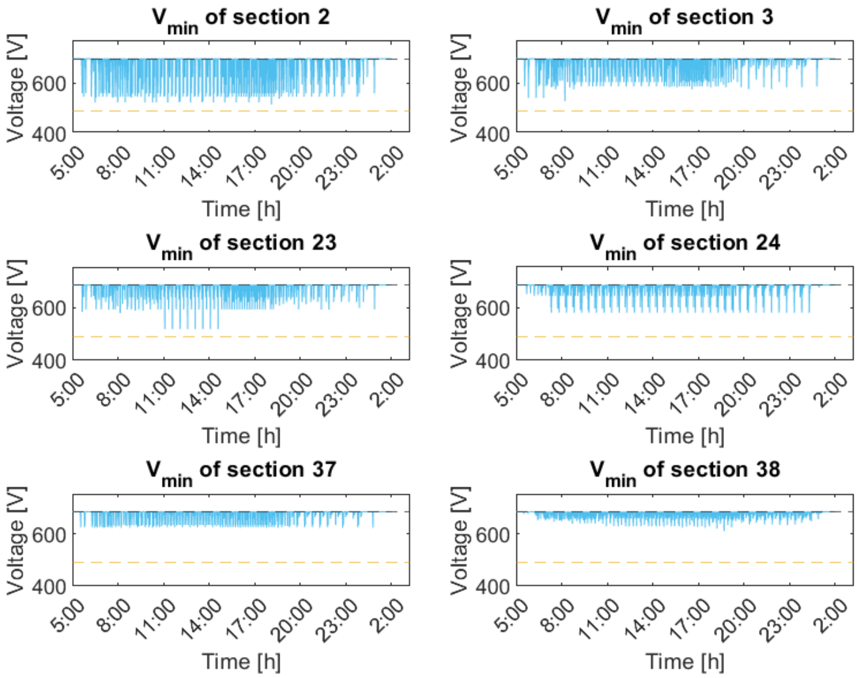


Figure C.11: Minimal section voltage for each section of line 352 during **day 200**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

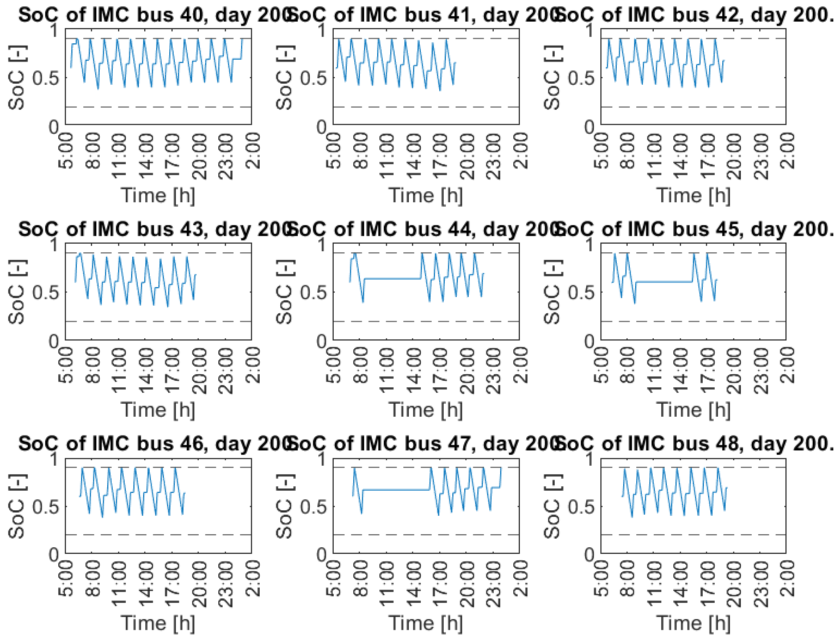


Figure C.12: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 200**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

C.4. Day 268

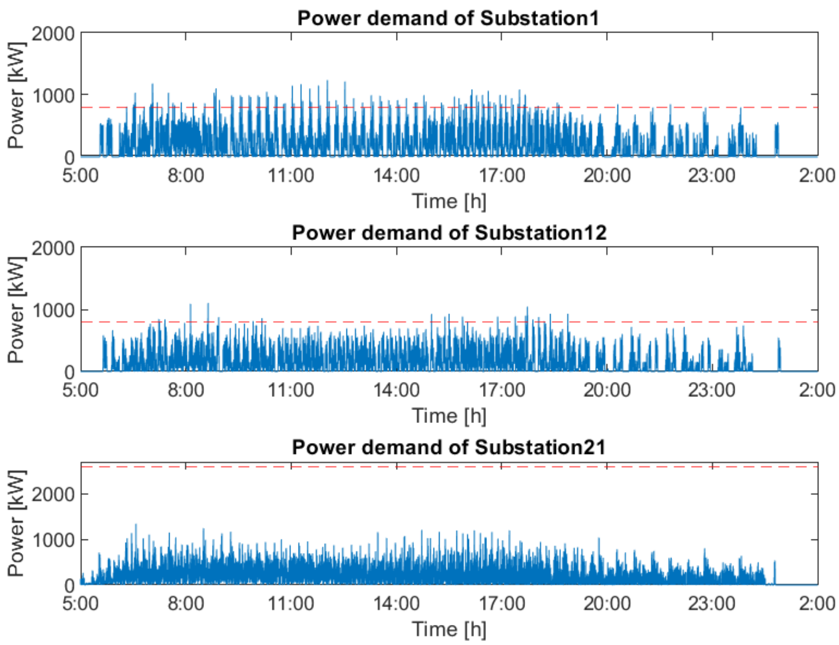


Figure C.13: Substation power demand during **day 268**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 scenario.

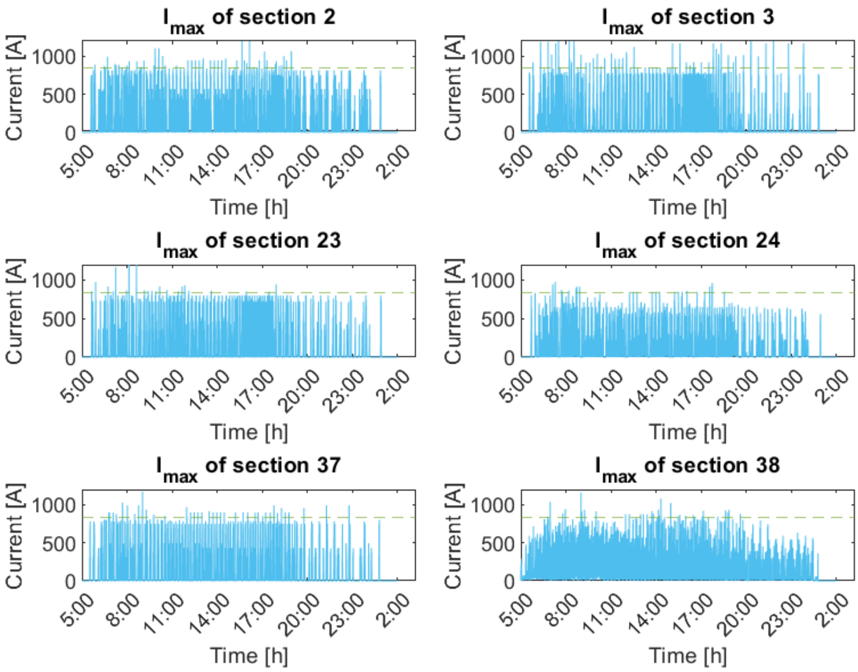


Figure C.14: Maximal current on each section of line 352 route during **day 268**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V3 scenario.

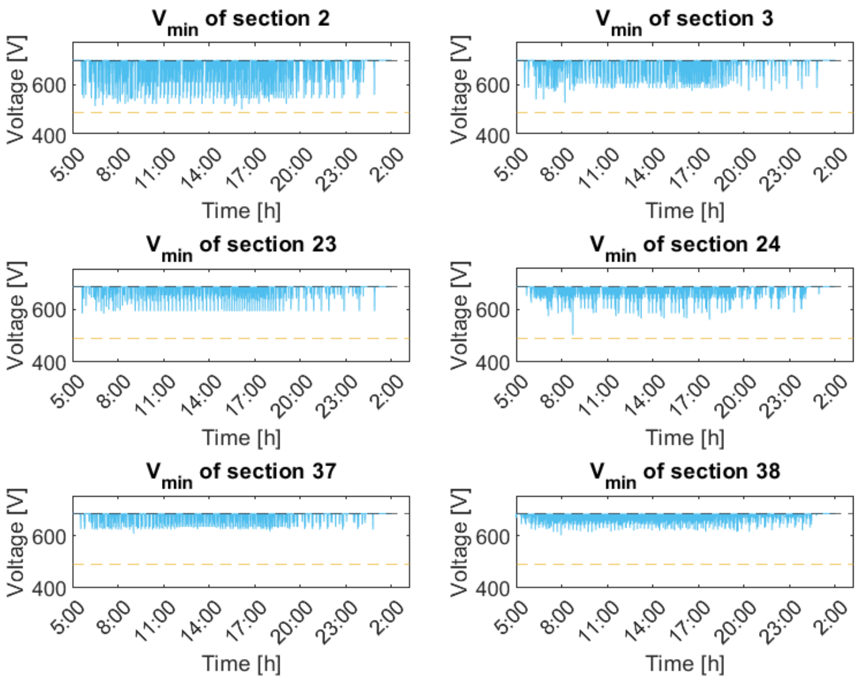


Figure C.15: Minimal section voltage for each section of line 352 during **day 268**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

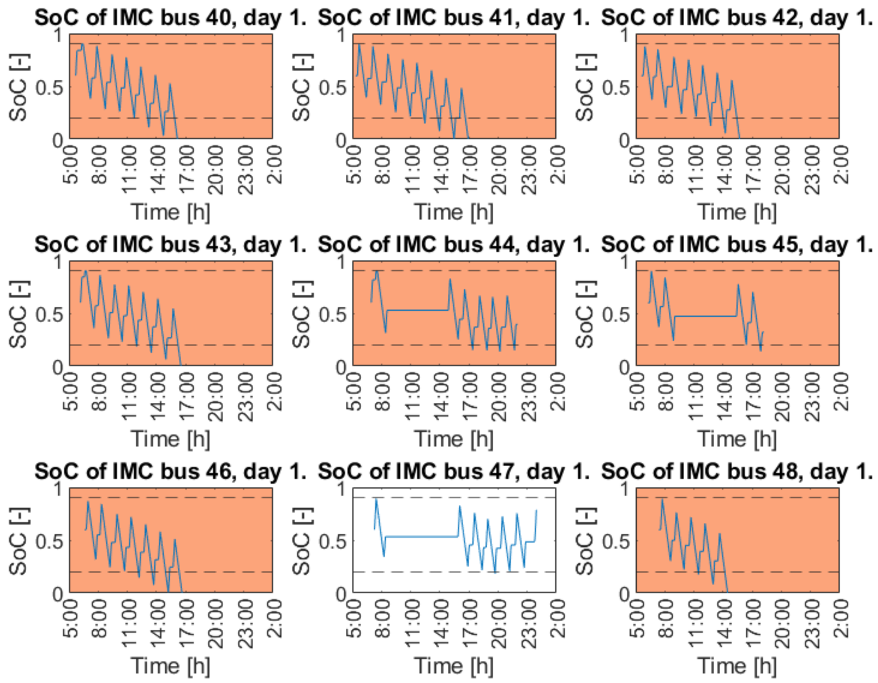


Figure C.16: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 268**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

C.5. Day 305

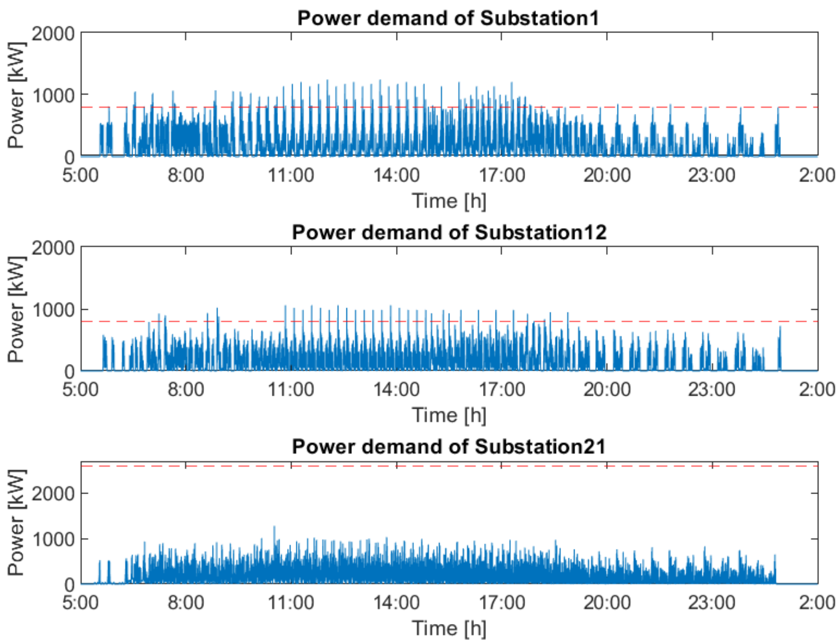


Figure C.17: Substation power demand during **day 305**. Horizontal dashed red lines represent power demand limit of the substation. Estimator V3 scenario.

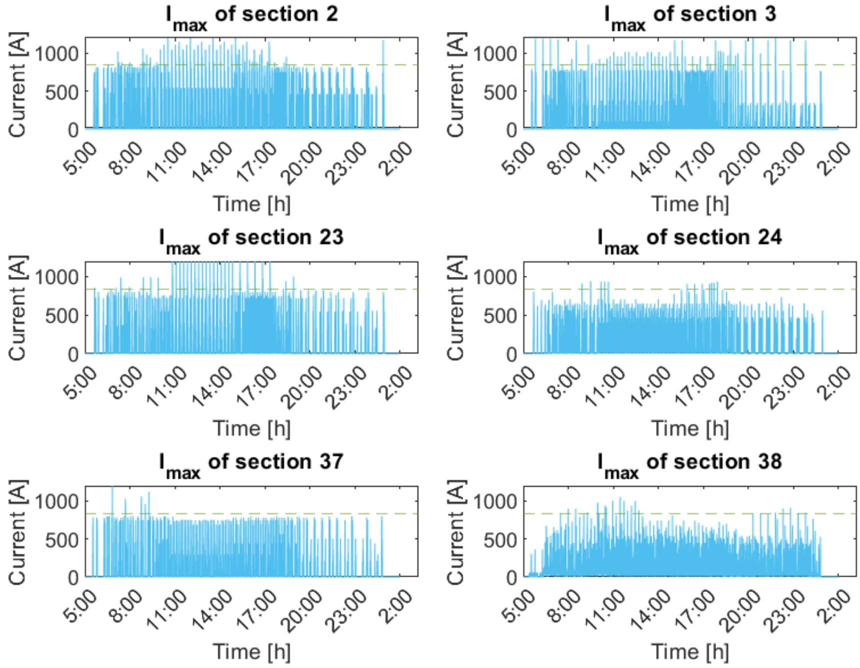


Figure C.18: Maximal current on each section of line 352 route during **day 305**. Horizontal dashed green lines represent maximal allowed current in the over-head lines of 840 [A]. Estimator V3 scenario.

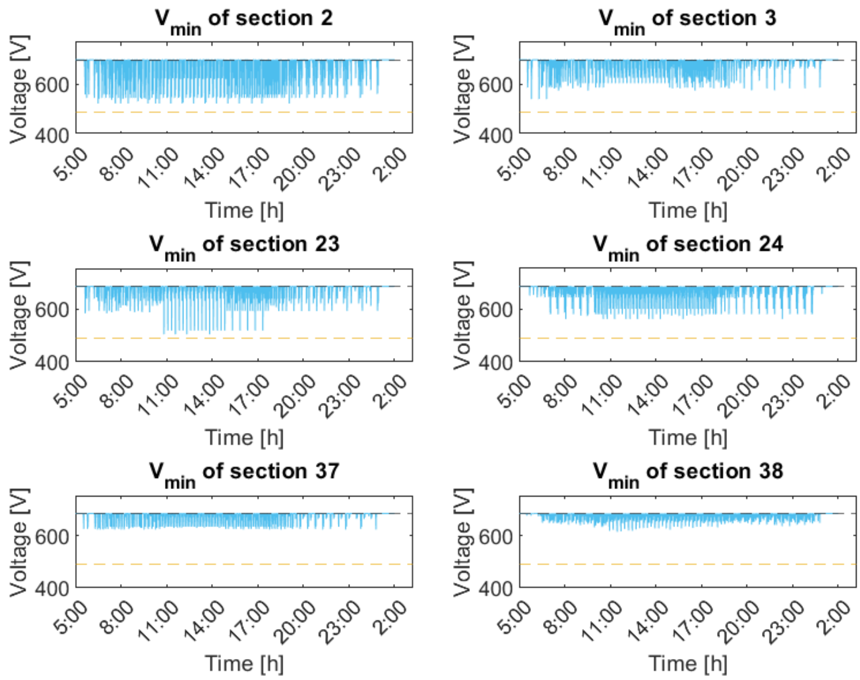


Figure C.19: Minimal section voltage for each section of line 352 during **day 305**. Horizontal dashed black lines represent nominal voltage of the substation. Horizontal dashed yellow lines represent minimal voltage allowed of 490 [V]. Estimator V3 scenario.

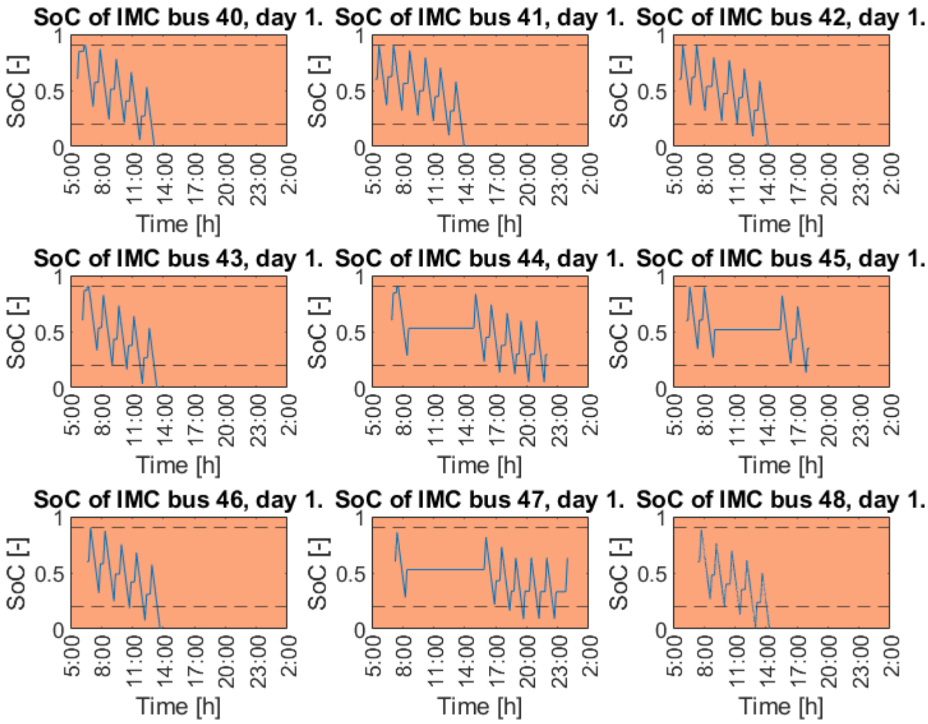


Figure C.20: State of Charge (SoC) for each IMC trolleybus of line 352 during **day 305**. Horizontal dashed black lines represent upper and lower limits of the SoC, 95% and 20%, respectively. Buses 44, 45 and 47 only operating in the morning and evening. Estimator V3 scenario.

D

Adaptability of estimator-supported Valley-Charging - 300 [kW] EV Charger

For the second simulation, the charging power of the EV charger was increased to 300 [kW]. The placement remained the same. From the substation 12 power demand in figure D.1, we can see that a 300 [kW] charger is much more complicated to integrate into the trolley-grid and that is even with Valley-Charging with estimator and not just conventional charging scheme. The amount of serious violations of 150% increased to 15, which means 13 more on substation 12. With 120% limit, the number rose to 270 breaches. Just the integration of such high-power charger could account to almost half of the substation limit. Based on the results, it would be advisable to use the 100 [kW] as it does not change the behavior on the trolley-grid that much.

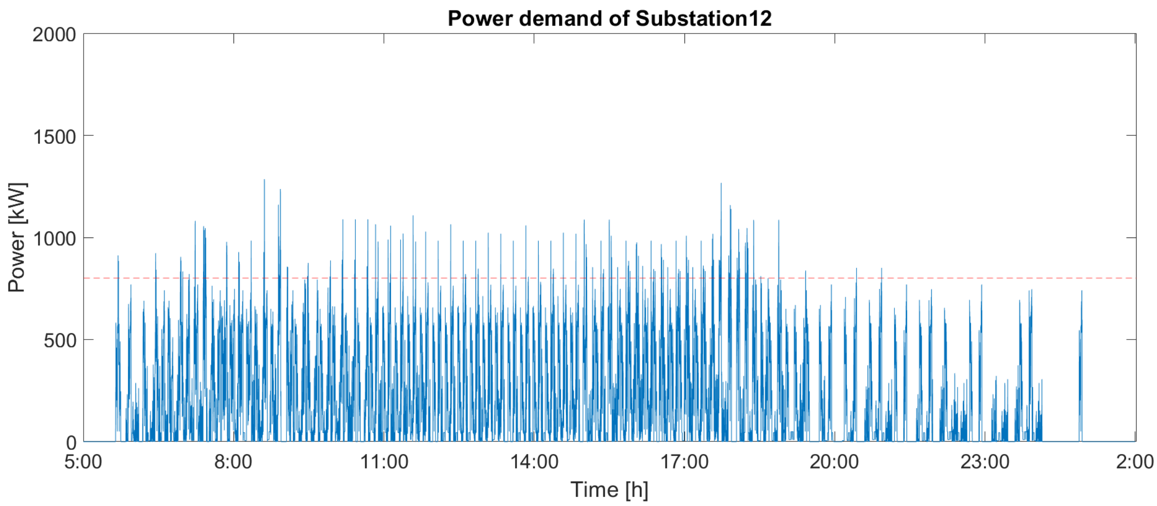
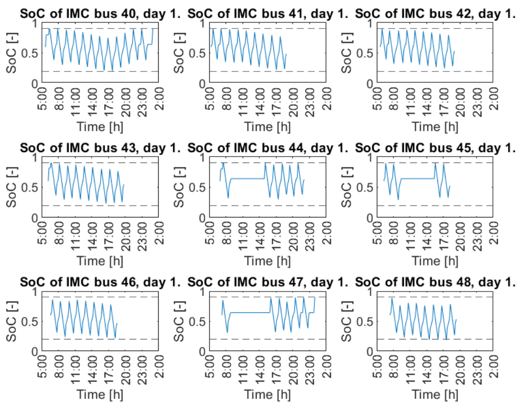


Figure D.1: Power Demand of substation 12. EV charger on section 24 at 600 [m]. EV charging power 300 [kW]. Red dashed line represents the limit of the substation of 800 [kW]

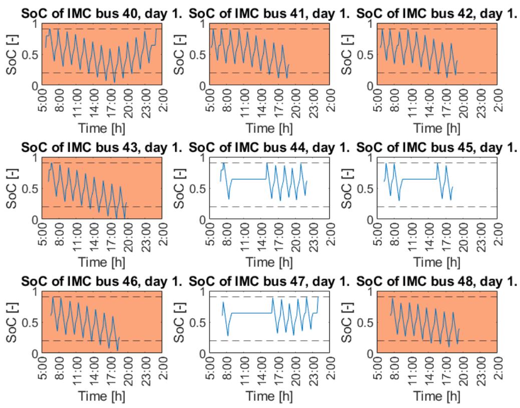
Even though, the power demand on the substation significantly increased, the estimator reacted to that new load on section 24 to some extent. It can be understood from the amount of energy collected per section in table D.1. The IMC trolleybuses were able to pick-up only 530 [kWh] by charging on section 24, which is 223 [kWh] less than without the 300 [kW] EV charger. That is equivalent to almost two fully charged on-board batteries. It also caused a difference in the total energy collected which decreased by 120 [kWh]. In this case, the conditional charging on section 38 proved to be very efficient as it was able to partially compensate for section 24. Nevertheless, the SoC of the IMC trolleybuses was affected negatively and most of the batteries dropped below the bottom limit of 20% SoC.

Table D.1: Energy collected per section. Comparison of the effect of 300 [kW] EV charger on the energy collected. Day 268

Charging Scheme	Energy Collected per Section [kWh]						Total
	24	23	2	3	37	38	
Valley-Charging	**752**	907	904	1059	635	451	4710
Valley-Charging + EV Charger	**524**	900	895	1087	644	646	4697



(a) Valley-Charging



(b) Valley-Charging + EV charger

Figure D.2: Comparison of SoC of IMC trolleybuses with Valley-Charging approach and with Valley-Charging with 300 [kW] EV charger on section 24. Buses 44, 45 and 47 only operating in the morning and evening. Data for 1.1.2020 (day 1)

E

Estimation of the maximal current in the overhead lines

The values of I_σ and V_σ give us information on the trolleybus parameters, meaning what the current and voltage of the trolleybus would be on this position if it is alone on the section. This subsection is going to introduce a new concept of P_σ which is especially useful in cases when it is known that the vehicle is not alone on the section. Unlike the first two concepts presented, P_σ should provide more insight into the global state of the grid.

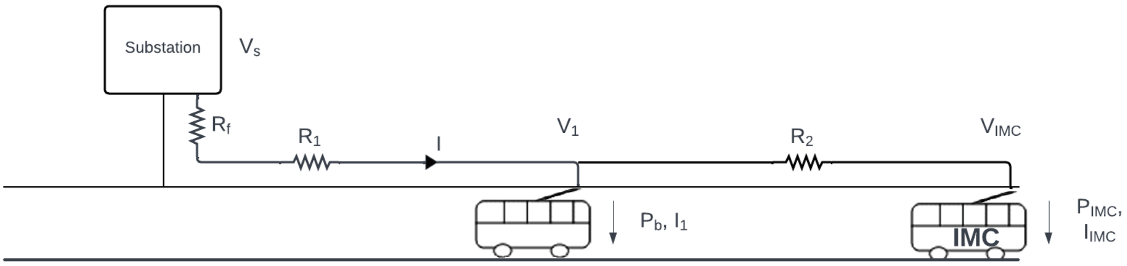


Figure E.1: Illustration of electrical path from substation to vehicle. Multiple vehicles on section. S - Substation, V_s - Substation nominal voltage, R_f - Feeder cable resistance, I - Current, R - overhead line resistance, P - Bus Power

Let's assume a traffic situation on a random section as it is depicted in figure E.1. There are two vehicles which one of them is an IMC trolleybus. As both trolleybuses are demanding a power supply from the substation, the overhead line conducts a current I which is divided in the first connection node into I_1 going into the regular trolleybus and I_IMC which continues through the rest of the overhead line towards the IMC trolleybus. This current is causing a voltage drop. If only the feed-in point and the two nodes where the trolleybuses are connected are taken into account, the magnitude of the voltage drop is the smallest at the feed-in point and keeps increasing with the distance from the feeder cable as the resistance is growing. That leaves the last IMC trolleybus with the lowest voltage that can be measured on the section. Now, based on the values of I_σ and V_σ we could determine whether the current and voltage the trolleybus measures match and thus figure out that there supposedly is at least one more vehicle connected. It would be very convenient to know what the total power demand on the section is and get the idea of the global state of the section. The value of P_σ suggests what the power demand on this position of the section has to be in order to measure such voltage drop. For that purpose, the same equation 3.40 can be used. It is just not desirable to find out the bus voltage V_b which is already known as V_IMC but the power P which is now the P_σ:

$$P_\sigma = \frac{(2V_\mathrm{b} - Vs)^2 - V_\mathrm{s}^2}{-4(R + R_\mathrm{f})} \tag{E.1}$$

where R stands for the total resistance of the overhead line between the vehicles and the substation, in this case $R = R_1 + R_2$. To provide an example, let's assume that both of the trolleybuses demand 100 [kW] and are approx. 600 [m] and 1200 [m] away from the substation, respectively. The voltage drops they would see are:

$V_{\text{feed-in}}[V]$	$V_1[V]$	$V_{\text{IMC}}[V]$
695	663	647

If the substation nominal voltage V_s is 700 [V], then the equation presented above gives us an estimation of 153 [kW]. This is the amount of power that would cause a voltage drop of 647 [V] exactly on the position of the IMC trolleybus. It can be seen right away that there is a deviation from the actual power demand which is 200 [kW] if only the traction demand of trolleybuses is of interest and 212 [kW] when also the transmission losses are included. To understand why it happens, the calculation will be done also for a case where the two trolleybuses are switched as in figure E.2.

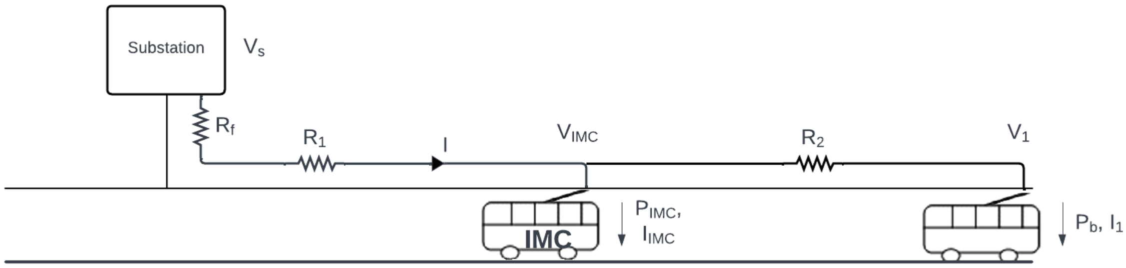


Figure E.2: Illustration of electrical path from substation to vehicle. Multiple vehicles on section. IMC trolleybus is closer to the substation than it was in figure E.1. S - Substation, V_s - Substation nominal voltage, R_f - Feeder cable resistance, I - Current, R - overhead line resistance, P - Bus Power

As the only parameter that changed is the position of the trolleybuses (but still the same distances from the substation), the voltage drops are the same for each node:

$V_{\text{feed-in}}[V]$	$V_{\text{IMC}}[V]$	$V_1[V]$
695	663	647

However, for the calculation of P_σ, the voltage V_b the bus measures and the magnitude of the resistance R is different and the result of P_σ is 202 [kW]. This number is much more promising than the previous one because it correctly predicts the amount of traction power demanded. The difference is in the position of the vehicles. In this case, the IMC trolleybus was the closer one to the substation of the two vehicles. The voltage V_{IMC} was then affected by the whole current I. As this vehicle now has full information such as the resistance and the voltage drop, the accuracy of P_σ is much higher. On the other hand, when the IMC trolleybus was placed at the end of the line, the voltage drop from V_1 and V_{IMC} (figure E.1) was only caused by the resistance R_2 and current I_{IMC}. The calculation takes the resistance $R_1 + R_2$ as the one causing the voltage drop which results in lower power necessary for that effect.

As P_σ provides understanding of what the total power demand could be, it might serve to estimate the total amount of current in the overhead lines. It could be determined by an equation for power where the actual bus voltage measured can be used:

$$I_{\text{est}} = \frac{P_\sigma}{V_b} \tag{E.2}$$

The quantity I_{est} can be understood as an estimation of what the maximal current can be. It has been also explained that the accuracy of this estimation depends heavily on the position of the vehicle. The closer to the substation, the lower the probability of having another vehicle between the IMC trolleybus and the feeder cable and even if that would be the case, the lower the resistances affecting the deviation would be.

To understand the dependency better, an experiment where one trolleybus, number 1, is kept at constant position of 1100 [m] from the substation and the other, number 2, is moved meter by meter to study the most scenarios possible.

$P_1[kW]$	$P_2[kW]$
300	100

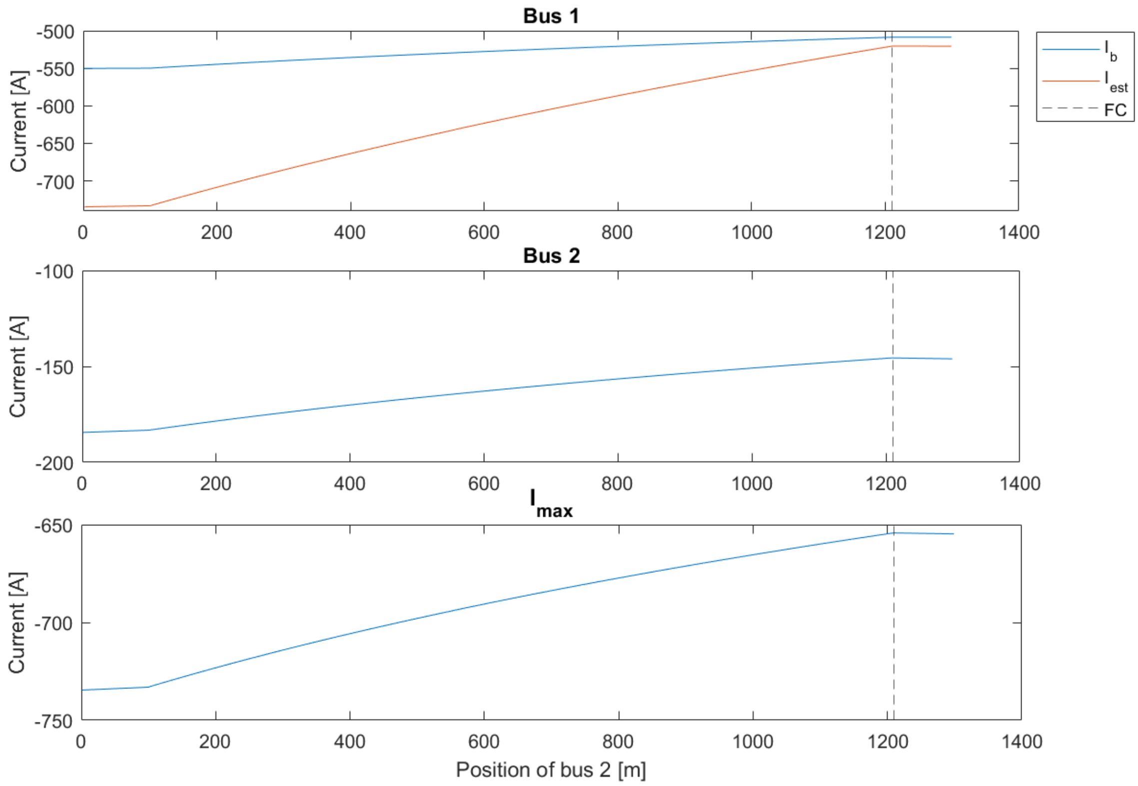


Figure E.3: Plots of bus currents I_{b} and maximal current estimation I_{est} based on position of bus 2. Substation nominal voltage 698 [V]. Feeder cable (FC) placed at 1210 [m] (vertical black dashed line) from total 1300 [m].

Figure E.3 shows the results of currents of bus 1 (constant position) for which also the maximal current is predicted and bus 2 which moves on the section. As long as the bus 1 is the closer to substation (up until 100 [m]), the estimation is very accurate as it the difference between I_{max} and I_{est} is almost 0 (figure E.4). The further from bus 1 and the closer to the substation bus 2 travels, the higher the error of prediction is. The reason for this error has already been explained. Another change of behavior can be seen once bus 2 passes the feeder cable and finds itself on the other side of the section from the feeder cable. The bus stops influencing the voltage drop and current that much and the estimation might not be relevant anymore.

As the accuracy actually decreases with the distance from the substation, the value of I_{est} can give another information. It can be seen that as both the vehicles are far away from the substation, the difference between the bus current and the maximal current estimation from the first subplot of figure E.3 is large. Understanding of this difference is crucial for further utilization of this concept. The higher the difference is, the more likely it is that I am not the only trolleybus contributing to the voltage drop and there is also another one drawing certain amount of power. In this case, two trolleybuses standing very far from the substation cause the voltage drop together as the maximal current has to go through more than a kilometer of overhead lines. If then a moment when bus 2 is close to the substation, the difference between the two currents is significantly smaller. The voltage drop caused by bus 2 close to the substation is rather negligible compared to the voltage drop bus 1 experiences. As solely the

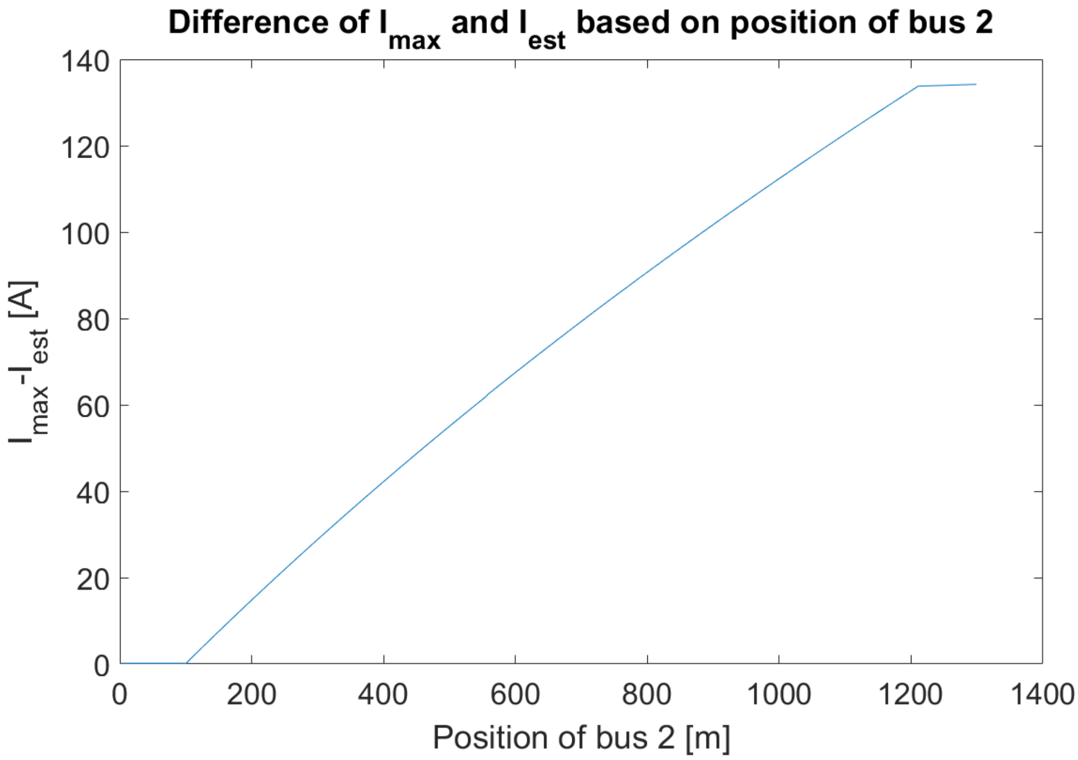


Figure E.4: Difference of maximal current I_{max} and maximal current estimation I_{est} based on position of bus 2. Substation nominal voltage 698 [V]. Feeder cable (FC) placed at 1210 [m] (vertical black dashed line) from total 1300 [m].

current dedicated for bus 1 goes the distance in the overhead lines, the estimation, although inaccurate, tells that it is bus 1 causing the voltage drop the most.

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