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A modular switching system as a flexible charging solution for a logistics terminal

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A modular switching system as a flexible charging solution for a logistics terminal

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Abstract

The ambition to move road transport from fossil fuels to electric energy is a large undertaking. One of the biggest challenges with making the trucks fully electric is to charge them. They are usually operated daytime, and the operations gives very little time for charging resulting in the power needed for daytime charging being in the high 100s of kW. A desired system implemented at the terminal would be a flexible system which provides charging in different power levels at different charging spots, matching the charging power needed of each individual truck charging at any given time.

This thesis investigates a modular switch matrix charger, using Elonroads electric road system as stationary charging ports, as a solution to charge a larger logistics fleet and compares it in flexibility, robustness, and costs to a more conventional fast charger model. The modularity stems from the charger being built with several dc-dc converters where each is connected via a switch matrix to each charging port. This enables the charger to divert as many converters as needed to every charging port in a flexible way, providing each charging spot with the unique power level each truck desires when charging. In the thesis a small scale prototype is also constructed to prove the switch matrix concept as a working solution.

The results shows that the charger with a switch system is a cheaper alternative, mainly due to the fewer numbers of DC-DC converters needed, while still being a more flexible and robust system compared to the conventional fast charger system. The cost of the switch model is heavily based on the number of switches in the system which correlates to the size of the whole structure. The small scale prototype also proved that the switch system is feasible to build.

Acknowledgements

This master thesis concludes my five years of study to become an electrical engineer at LTH. With that done I want to give my thanks to those who have aided me during the last half year. I want to thank my supervisors Kim Malmberg Svedmark and Mats Alaküla for guiding me in this work. Mats who through his courses in power electronics and Electric hybrid technology cemented my interest in these subjects and who put me in contact with Elonroad. Kim for his continuous support and very helpful discussions. Without his guidance and expertise this thesis would have been a lot harder. Also thanks to Elonroad who has allowed me to not only to do this master thesis with them but also work in the factory for sometime before the thesis started. All around a great team which has been a huge inspiration to see work and I am glad to have got to know. Special thanks to Philip Abrahamsson for being bombarded with my questions and answering each one with enthusiasm, and thanks to Archisman Datta for helping me with the converters for the prototype build.

Contents

1 Introduction

Logistics terminals in Sweden can accommodate up to over 100 trucks from 3.5 ton to over 20 ton of gross vehicle weight (GVW). The ambition to move road transport from fossil fuels to electric energy requires that almost all these trucks are fully electric. One of the biggest challenges with making them fully electric is to charge them. Being commercial vehicles, they are usually operated daytime and the operation gives very little time for charging. Thus, it must be assumed that most of the charging must be made at the logistics terminal, and most of that nighttime. The power needed for nighttime charging is relatively low, in the 10s of kW, with a few exceptions for trucks that deliver and pick-up goods during the evening or night. During the day, the trucks that drive the longest routes will consume more power than the provided nighttime charge and will have to be charged during the day as well. To not waste valuable time the charging time must be low, thus the charging power provided will be in the 100s of kW.

Assuming all charging will be done from the logistics terminal, the terminal will need to be able to provide both nighttime charge (slow charge in the 10s of kW) and daytime charge (fast charge in the 100s of kW). The easiest solution would be to provide the maximum number of charging power at each charging spot, i.e fast chargers at each charging spot. However, such a solution would be expensive since the cost of chargers is proportional to the installed power of the system. A cheaper solution could be to have dedicated nighttime and daytime charging spots. This is however impractical due to a logistics terminals limited space and offers little flexibility in the system as to where the trucks can charge during the day.

Instead, a desired system would be a flexible system which provides charging in different power levels at different charging spots, matching the charging power needed of each individual truck charging at any given time. Such system would be a modular charger with a switch system, meaning the charger is built with several dc-dc converters there each is connected via switches to each charging spot. This enables the charger to divert as many converters as needed to every charging spot in a flexible way, providing each charging spot with the unique power level each truck desires when charging.

Also, considering a logistics terminals limited available area, a conventional approach with charging poles and cables is undesirable as the poles and cables create an unnecessary complex environment to navigate and run the risk of being damaged. Thus, each charging spot should be equipped with an electric road system (ERS), an electric rail on the ground, which is able to provide conductive charging under the vehicle without the need for cables.

1.1 Background

This thesis is an in-depth continuation on a previous investigation about power systems for a logistics terminal with only fully electric vehicles. In the earlier project, Bring logistics terminal in Malmö was investigated. The terminal hosts 55 trucks, 40 of which are 3.5 ton trucks and 15 of which are 7-20 ton trucks. By taking the truck's daily drive pattern and assuming their battery size, the needed charging power for each individual vehicle could be estimated as well as the terminals' total power output to facilitate that need. Two different charging systems were also investigated and compared by cost. The systems were conventional plug-in chargers and a modular switch system using an ERS. Of these two a conclusion was reached that the modular system using ERS tracks had less production cost and was better suited for a logistics terminal due to the terminals' limited space. This modular system is what this paper will delve deeper into and investigate if it is possible to build the proposed switching matrix. The work will also include a prototype build of the system on a small scale to verify the switch matrix as a working solution.

1.1.1 Previous study

From the previous mentioned project, the total charge power needed for nighttime and daytime charging can be seen in Table 1. The maximum power output the terminal must facilitate is therefore 3072 kW, about 3,1 MW, that is if all trucks charge at the same half hour at the terminal. For nighttime charging all trucks charge for 12h at the terminal. For the Bring terminal a total of 35 of the 55 trucks would need additional charge during the day and the charge power needed to fully charge ranges from 8 kW to 480 kW. It is these 35 trucks that is the main driver behind the size of the charging station since they together consume more than 7 times more power when charged for 30min during the day compared to when all 55 trucks charge for 12h during the night.

The maximum charge power a charging station must provide to be able to charge any vehicle of the given weight is illustrated in Table 2.

Truck [ton]	P_{night} [kW]	P_{day} [kW]
3.5	163	1242
7-20	243	1830
Sum	406	3072

Table 1: *Power consumption when charging at the terminal*

Truck [ton]	P_{night}/truck [kW]	P_{day}/truck [kW]
3.5	5	70
7-20	15	480

Table 2: *Max charge for the different trucks*

The conceptual connection of the modular switch charger is shown in Figure 1. The power modules, AC-DC converters or DC-DC converters, are connected to the ERS tracks via the switch matrix. Each time a horizontal line and a vertical line cross there is a node. The node, being a switch, can connect any number of power modules (horizontal lines) to an ERS track (intersecting vertical line). However, a power module cannot be connected to two or more ERS tracks at the same time. Thus, an vertical line in the figure can be connected to several horizontal lines but a horizontal line cannot be connected to several vertical lines. The number of nodes, i.e switches in the system, are dependent on the number of modules times the number of ERS tracks. Since the Bring terminal had 55 vehicles and all needed to charge during the night, the number of ERS tracks needed is 55.

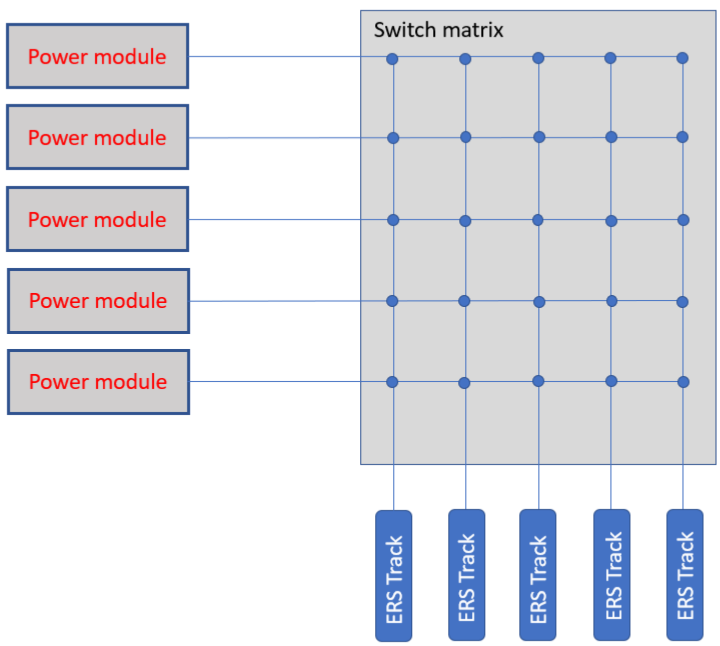


Figure 1: *The modular charger with the switch system*

For the power modules in this previous study AC-DC converters were chosen ranging in size according to Table 3 with their respective production costs at a high volume of units/year (>1000) [14]. However, in this thesis isolated DC-DC converters will be investigated instead. The reason is that the DC-DC converts can be connected to a larger common AC-DC feeding station which is placed outside of the terminal.

AC/DC converter cost	
kW	€/kW
30	30
50	25
100	22
150	20

Table 3: *AC-DC converter power levels and their respective costs*

Different combinations and numbers of converters were investigated as shown in Table 4. The number of modules in each configuration are chosen specifically for the Bring terminal to get the available power as close to 3.1 MW as possible while not being below it. As seen in Table 4 each combination is calculated twice with different ratios of larger power modules versus smaller power modules. The configurations are to investigate the cost of having a higher power "resolution" for the charger. Smaller power modules give smaller power steps when increasing/decreasing power which gives a higher resolution when dividing the power between the vehicles. With larger power modules the resolution is thus lower. Configuration A investigates a system with a higher ratio of large power modules and configuration B investigates a system with a higher ratio of smaller power modules. Configuration C looks at a system with a wider combination of modules having both smaller, medium and larger power modules. A fourth type of configuration was also investigated where only one type of power module would be installed. The result can be seen in Table 5 where the table is sorted by lowest cost. The number of switches given a specific configuration as well be seen in Table 5. Constructing the charger with larger power modules, or a combination of a high ratio of larger modules with a lower ratio of smaller modules, costs less and needs fewer switches. Although the trade-off is the power resolution being lower.

Cofiguration	power	amount of modules	total output power [kW]	cost €
A	30	13	390	11700
	100	27	2700	59400
	sum		3090	71100
B	30	47	1410	42300
	100	17	1700	37400
	sum		3110	79700
A	30	13	390	11700
	150	18	2700	54000
	sum		3090	65700
B	30	47	1410	42300
	150	12	1800	36000
	sum		3210	78300
A	50	8	400	10000
	100	27	2700	59400
	sum		3100	69400
B	50	28	1400	35000
	100	17	1700	37400
	sum		3100	72400
A	50	8	400	10000
	150	18	2700	54000
	sum		3100	64000
B	50	28	1400	35000
	150	12	1800	36000
	sum		3200	71000
C	50	8	400	10000
	100	11	1100	24200
	150	12	1800	36000
	sum		3300	70200
only one type of module	30	103	3090	92700
	50	62	3100	77500
	100	31	3100	68200
	150	21	3150	63000

Table 4: *Different module configurations and their costs*

cost in order	configuration	amout 30kW	amount 50 kW	amount 100kW	amount 150 kW	OBC cost €	amount of switch nodes
1					21	€ 63 000	1155
2	A		8		18	€ 64 000	1430
3	A	13			18	€ 65 700	1705
4				31		€ 68 200	1705
5	A		8	27		€ 69 400	1925
6	C		8	11	12	€ 70 200	1705
7	B		28		12	€ 71 000	2200
8	A	13		27		€ 71 100	2200
9	B		28	17		€ 72 400	2475
10			62			€ 77 500	3410
11	B	47			12	€ 78 300	3245
12	B	47		17		€ 79 700	3520
13		103				€ 92 700	5665

Table 5: *Sorted table of power module configuration with the number of needed switch nodes*

The previous project did the same calculations for daytime charging windows of 1h, 1,5h and 2h. The conclusion being that if it is possible to have the trucks to charge for a longer time the number of converters needed would decrease and thus the number of switch nodes would also be decreased as well as the total cost of the system.

1.2 Goals

The goal of this master thesis is the following:

1. Modeling and cost analysis of a charger based on the modular system which been initially investigated in the project by Axel Stenström with the IEA department at LTH in the fall of 2021.

2. Construction and verification of a switch node in the switch matrix that is part of the charger.

1.3 Method

To achieve these goals the following approach was chosen for the thesis.

1. Literature study and review of data sheets on existing charger technologies.

2. Modeling and cost analysis of the charger structure based on calculated values of the current and voltages that exist on a logistics terminal. This will be done in three steps:

    - Charge time calculation of the individual trucks for different converter sizes and installed power in the charger. The converters used are isolated bidirectional converters which 1) provides safety in form of galvanic isolation, and 2) allows for vehicle to grid (V2G) connection.

  - Using the calculated charging times to simulate a charger with the different converter sizes and installed power to find the optimal power resolution.
  - Cost calculation of a full scale charger structure for each simulated case. The cost calculations are then compared with a conventional fast charger system.

3. Construction of a small scale prototype with testing and verification with real and believable current levels.

2 Theory

2.1 Charger structure

The structure of a single power module (from Figure 1) can be seen in Figure 2 [5]. The general principle of a charger is to convert AC power from the grid to DC power to charge the battery on the vehicle. With the series of power electronic devices, the charger can convert 400 V_{ac} (50Hz) grid input to charge batteries ranging from 150 V_{dc} to 920 V_{dc}. Most electric vehicles have an on board charger (OBC), a small AC-DC converter, which enables them to plug in directly to the grid i.e. a standard household AC receptacle to charge. This however is slow low power charging. To facilitate high power charging, which is needed for fast charging, a much larger AC-DC converter is needed which can supply DC directly to the battery on the vehicle [36]. For a DC charging station, the AC-DC converter is therefore outside the vehicle. As seen in Figure 2 [5] the off-board charger consists of a grid connection, rectifier, inverter, HF transformer and then again a rectifier and current controlled DC-DC converter. Where the HF inverter, HF transformer and the rectifier with a current controlled DC-DC converter converter together is a full bridge isolated bidirectional DC-DC converter.

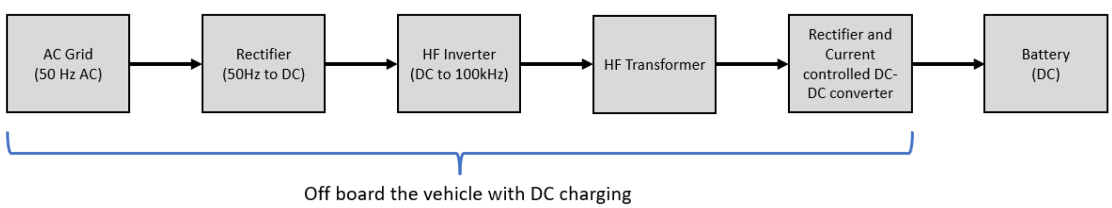


Figure 2: *Structure of an EV charger, both on-board and off-board.*

2.1.1 Isolated bidirectional converter

An isolated bidirectional converter is a converter that allows for a vehicle to grid connection, meaning when a vehicle is grid-connected it is able to provide power from its battery back to the grid. The block diagram of Figure 2 can be expressed as the circuit diagram in Figure 3. Bidirectional transmission is achieved by the use of controllable devices such as MOSFETs (S1-S14). The inductances (L) and capacitances (C) acts to dampen and/or remove resonance frequencies from the circuit making the DC output smooth [29]. In forward mode, from the high voltage side, the AC voltage has been rectified to DC which is then inverted to AC with much higher frequency (kHz), determined by the switching of the MOSFETs. The transformer acts as galvanic isolation, providing both personal safety but also for immunity against electrical noise [36]. Then on the low voltage side after the transformer, the AC voltage is rectified again to DC which is stepped down with a buck-boost converter to provide charge to the battery [15]. In reverse mode, from the low voltage side, the direction is reversed. The battery's DC voltages is stepped up with the buck-boost converter which is then inverted to HF (high frequency) AC voltage. After the transformer the HF AC voltage is rectified to DC voltage which is then again inverted to three phase AC voltage with a frequency of 50Hz, which is the frequency of the grid.

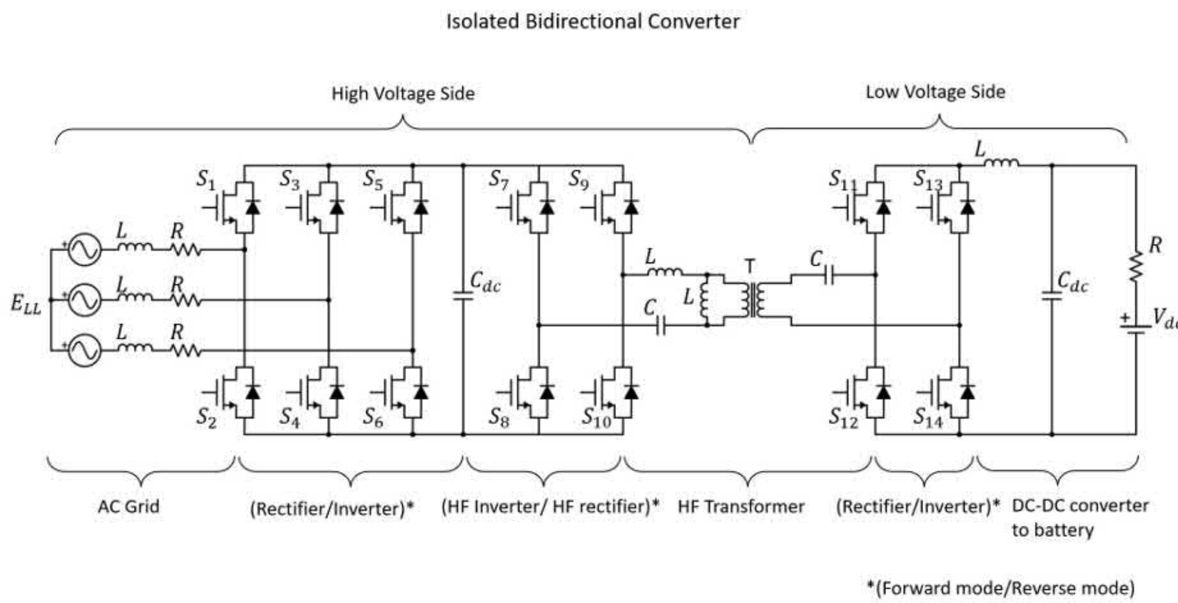


Figure 3: *Circuit diagram of an isolated bidirectional DC-DC converter*

As mentioned, the full circuit of the isolated bidirectional converter can be seen as a AC-DC converter (rectifier on the high voltage side) connected to a full bridge isolated bidirectional DC-DC converter (the HF inverter on the high voltage side and the HF transformer together with the rectifier and DC-DC converter on the low voltage side). The high voltage rectifier can thus be separated and used as a common rectifier for several full bridge isolated bidirectional DC-DC converters, illustrated in the block diagram in Figure 4. Hence why this thesis will focus on the DC-DC converters when building the charger station and not complete AC-DC converters which the previous study did.

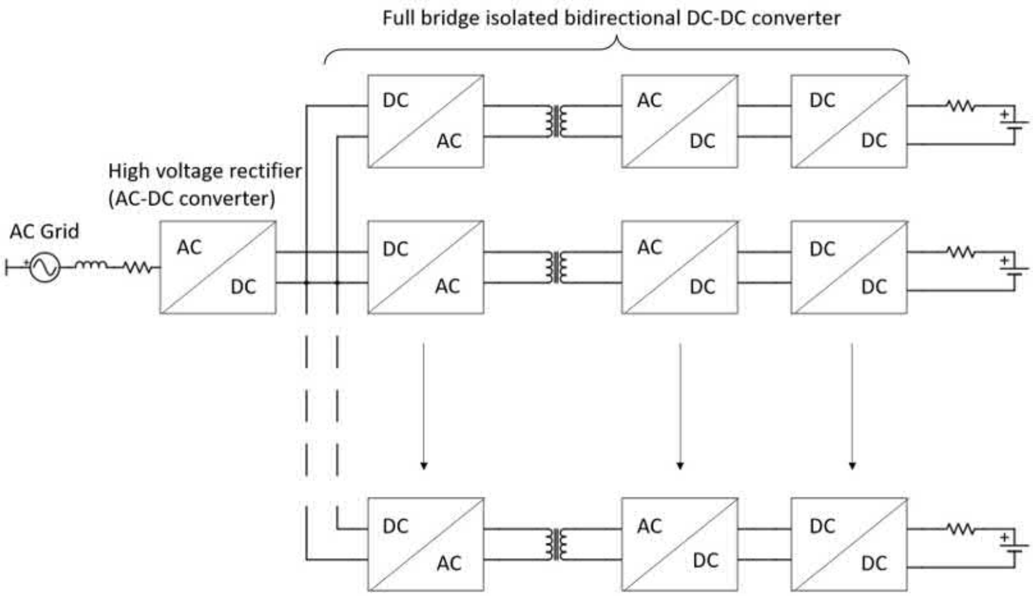


Figure 4: *Several isolated bidirectional DC-DC converters connected to a common AC-DC feeding station*

2.2 Modular design

Modular design of chargers means that a charger is built with several smaller power converters in parallel, each contributing to the total power output of the charger. The modular design is easy to scale up as more converters can be placed on the stack to increase the power output. The parallel configuration of the modules favours the supplying of high charging currents needed in high power charging while the modules share the same voltage. It also allows the charger to cater to different charging levels since the modules will be able to provide power in steps [9]. For example, a 150kW fast charger modular built with 50kW DC-DC converters can provide power in three steps of 50kW up to 150kW. Another advantage of parallel modules is if one fails the rest still works but with a reduced total power output [32]. In the next subsections a couple of charging applications with modular charging will be described.

2.2.1 Sequential charging

Instead of having a power cabinet containing the power modules for each charger, or every charger having their own power modules, a single cabinet can pair up with two or more charging poles allowing two or more vehicles to charge in sequence. When the first vehicle in the sequence starts charging at one of the chargers, the power cabinet will deliver its full power to the vehicle. When that vehicle is done charging the next one starts charging and so forth. The benefit of sequential charging is that each vehicle is charged with high power, allowing each vehicle to be charged quickly, maximizing their availability. The grid connection is smaller, since the power is limited to a single cabinet and is divided in sequence to each vehicle. Less infrastructure is also needed since all the modules are placed in a single cabinet and not in each charging pole. [2]

2.2.2 Limited grid capacity

If a site has more power installed in all charging stations together than the available grid capacity a control box can be configured with the modular DC chargers to help divide power as needed. For instance, a logistics terminal with a limited grid capacity of 300 kW with four 150 kW charging stations. The station could use two of the charging stations to charge two vehicles needing 150 kW. If a third vehicle arrives needing to charge 100 kW there would not be any available grid capacity left even though the terminal has enough installed power. Instead of allowing the vehicle to wait and having two charging stations empty, a control box could decide to divide the power to allow all three vehicles to charge with 100 kW. Thanks to the chargers being modular it is possible to disconnect modules to output less power as well as connecting modules to output more power. This makes for a flexible scalable system which lowers the needed grid connection. [1]

2.2.3 eMotion grid solution

Hitachi together with ABB has developed a modular fast charging solution suited for logistics terminals and bus terminals, in which several modules are connected to one high power rectifier and a grid transformer placed together inside a container like housing. This solution significantly reduces the amount of space and cabling needed compared to a conventional approach where each charging station is its own fast charger with its own grid connection. With rectifiers varying in power size from 1 MW to 3 MW and the modules ranging in size from 50 kW, 100 kW, 150 kW and up to 600 kW several different configurations could be made depending on the terminal's requirements. From 1MW rectifier and ten 100 kW power modules to 2.5 MW rectifier with twenty 150 kW power modules. The power modules can be connected to create individual chargers in the container. The chargers are then individually connected to charging points with single or double plugs. A 2 MVA grid connection with a 1.75 MW rectifier could for instance be connected to 20 2x50 kW chargers (two 50kW power modules connected to build one charger). With charging points with double plugs this would allow 40 vehicles to charge in parallel, each receiving 50kW power, or to charge sequentially, each pair at a charging point receiving 100kW power in sequence. This setup is illustrated in Figure 5. [30], [6], [3]

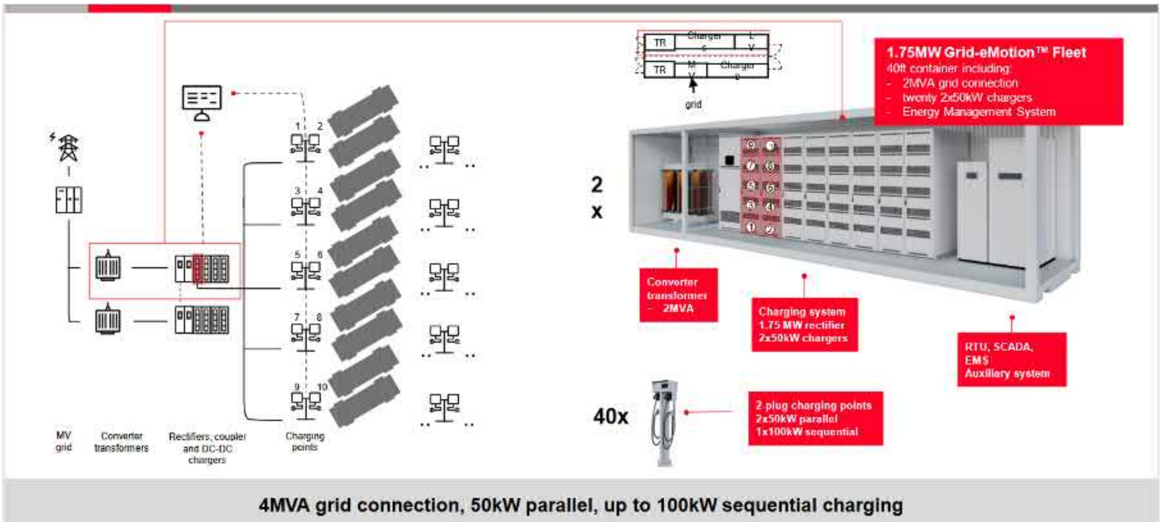


Figure 5: *Hitachi and ABBs eMotion grid solution*

2.3 Switch system

A switch system, like in Figure 1, is no new idea. In 2013 the company Tesla Motor INC published their patent on the concept of a charging station which includes a switching system. The patented system proposed a charging station with several charging ports and several power stages coupled together with switches. Each charging stage would be a power converter and each of those would provide a portion of the charging stations maximum power. Figure 6 illustrates the charging station concept. The charger is coupled with an AC power source (301) which powers the power modules (303-311). The modules, connected in parallel, are each connected to the charging ports (313-314) via the switch system (319) which is able to divide the power from the modules to the ports as need be. The power modules are grouped such that the blocks are able to provide equal amounts of power and can thus distribute power in four levels: 0, $\frac{1}{3}P_{max}$, $\frac{2}{3}P_{max}$ and P_{max}, where P_{max} is the maximum available power of all power blocks if connected to a single port. [33]

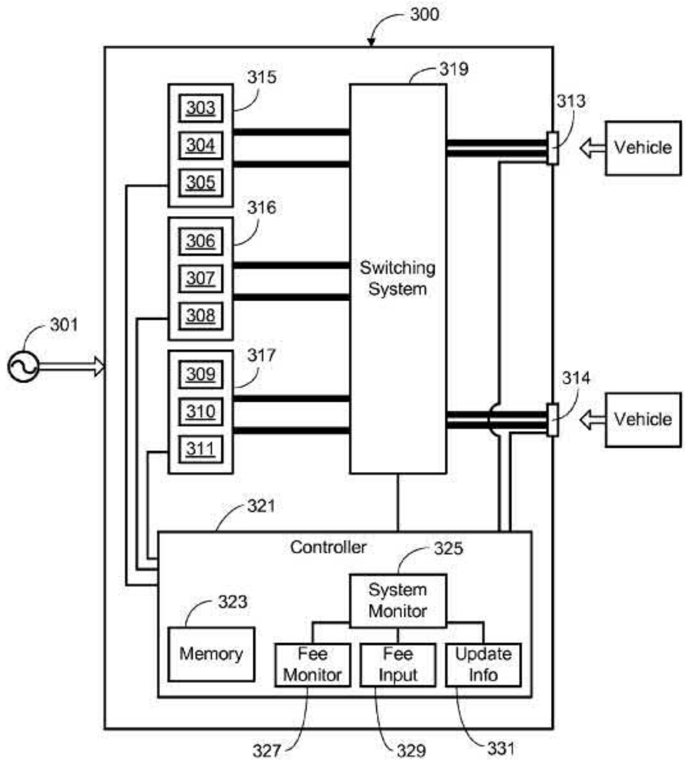


Figure 6: *Charging station with a switching system*

Two suggested switching systems are illustrated in Figure 7 and Figure 8 depending on what type of switch is used. Figure 7 system uses 12 on/off switches which are able to provide any combination of power output to the charging ports. By closing 501 and 503 power block 315 is providing power to charging port 313, and by closing 506, 508, 510 and 512 power block 316 and 317 is providing power to port 314. Alternatively in Figure 8 the switches in use are two-position switches. For the power blocks to connect to charging port 313 the switches should close the 'A' contacts and to connect to port 314 they should close the 'B' contacts. [33]

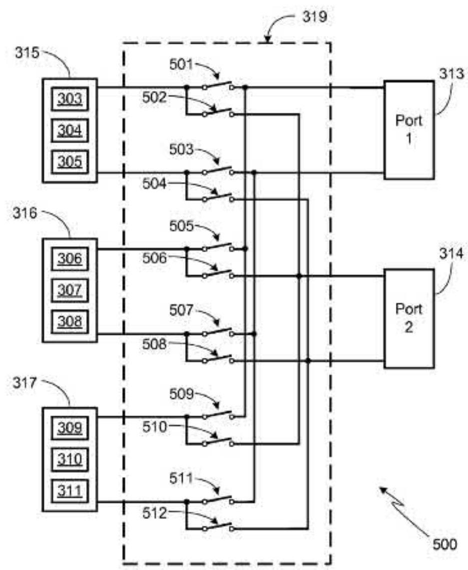


Figure 7: *Switching system with on/off contactors*

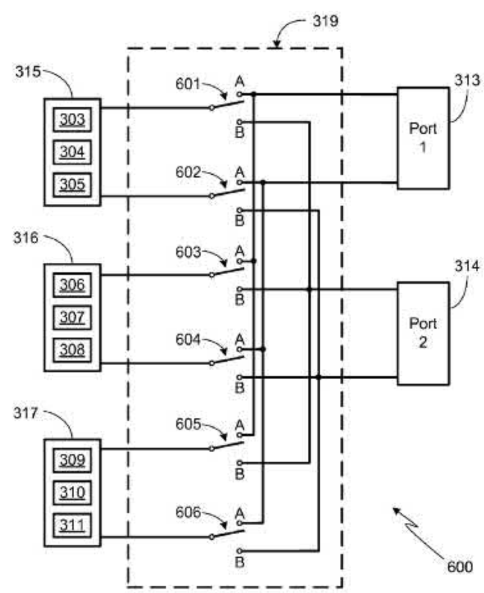


Figure 8: *Switching system with two-position contactors*

In Figure 9 each power module is connected to switches in the same configuration as Figure 7 without grouping the modules together in power blocks. The number of switches needed are tripled from 12 to 36 but smaller power steps and more flexible power distribution in the system is achieved. The configuration used in Figure 8 could also be used to reduce the number of switches. It would still be triple the amount compared to using power blocks, 18 switches compared to 6. All systems are designed to allow more power modules and charging ports to be added. [33]

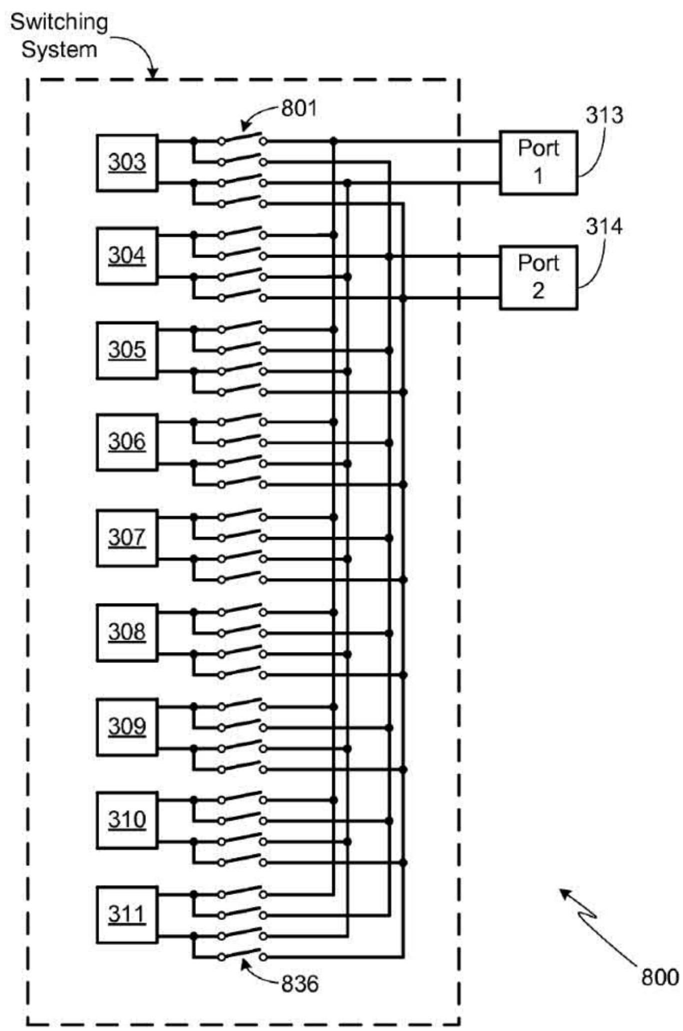


Figure 9: *Switching system without power blocks*

3 Modelling the charger system

The modelling of the charger is made using the daily driving patterns of the trucks from the Bring terminal as a reference point. From the previous project the energy of the trucks to complete their daily drive is known and is illustrated in Table 6. In the previous project the actual battery sizes for the trucks were assumed to be 80kWh for the 3.5ton trucks and 300kWh for the 7-20ton trucks. The usable battery is hence the available battery between 10% SoC and 80% SoC, which means a truck should at the latest start to charge above 10% Soc and end their charge at 80% SoC. The delimitation is due to battery health since charging bellow 10% and above 80% could damage the battery [5].

GVW (ton)	Number of trucks	Usable Battery Size [kWh]	Energy Consumption [kWh]	Charge Needed [kWh]
3.5	4	56	60	4
3.5	5	56	75	19
3.5	15	56	90	34
7-20	5	210	225	15
7-20	3	210	300	90
7-20	2	210	375	165
7-20	1	210	450	240

Table 6: *Daily energy consumption and charge needed for the various trucks*

The charger is modelled by simulating how the charging time and utilization of DC-DC converters differ between five different sizes of converters, 25kW, 50kW, 100kW, 150kW and 200kW, and four different total installed power levels of 1MW, 1.5MW, 2MW and 3MW. The cases are for example, a charger system constructed with 25kW converters to a total of 1MW installed power to be divided among 55 charging spots, a charger system constructed with 25kW converters to a total of 1.5MW installed power to be divided among 55 charging spots etc, up to a charger system constructed with 200kW converters to a total of 3MW installed power to be divided among 55 charging spots. Each case is also simulated two times to find what priority of charging should be used for the trucks. In one scenario the trucks that need the most power charge first and in the second scenario the trucks that need the least power charge first.

3.1 Charge time

Assuming the daytime charging takes place at lunch, after half a day's work, and that the battery consumption is homogeneous over the day, the energy consumed at the time of charging should be half of the given Energy Consumption from Table 6. The state of charge at any given time is calculated with the equation:

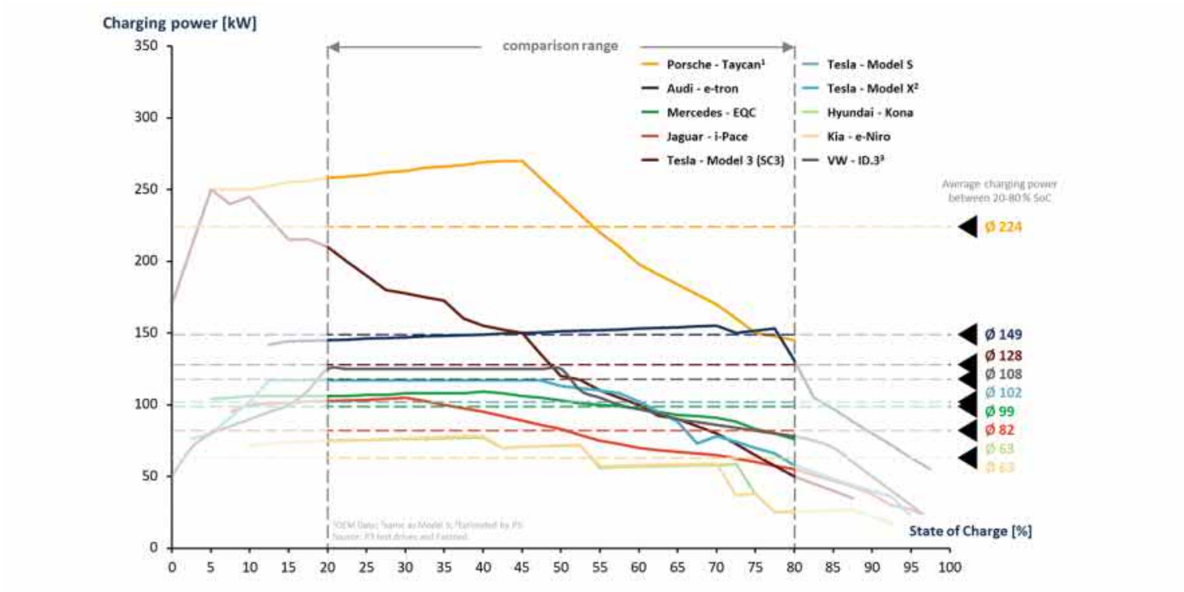
$$SoC\,[\%] = \frac{Current\ battery\ level; [kWh]}{Actual\ battery\ size\,[kWh]} \quad (1)$$

And thus both the SoC at the time of charging and after charging is calculated and illustrated in Table 7.

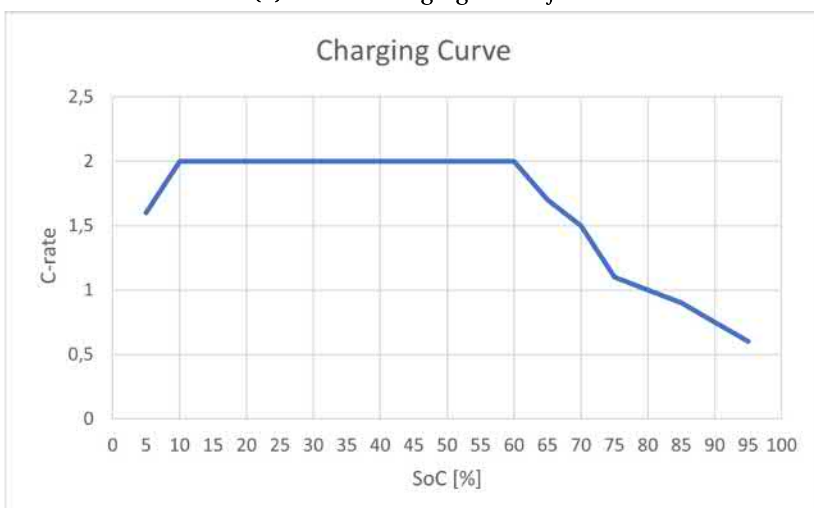
GVW (ton)	Number of trucks	Consumed battery at lunch [kWh]	Batt lvl at lunch [kWh]	Batt lvl after lunch [kWh]	Start SOC [p.p]	End SOC [p.p]	Diff [p.p]
3.5	4	30	34	38	0,425	0,475	0,05
3.5	5	27,5	37,5	56,5	0,331	0,569	0,238
3.5	15	45	19	53	0,238	0,663	0,425
7-20	5	112,5	127,5	142,5	0,425	0,475	0,05
7-20	3	150	90	180	0,3	0,6	0,3
7-20	2	187,5	52,5	217,5	0,175	0,725	0,55
7-20	1	225	15	255	0,05	0,85	0,8

Table 7: *SoC after a half days driving*

Knowing the SoC, the power usage and charging time for the trucks is calculated according to a charging curve. Using existing charging curves for a variety of cars, seen in figure 10a [11], a charging curve for the trucks is derived as in figure 10b.



(a) *Known charging curves for cars*



(b) *Derived truck charging curve*

Figure 10: *Charging Curves*

The y-axis in 10b is in C-rate [5] which is defined as,

$$C = \frac{charging\ power\ [kW]}{battery\ size\ [kWh]} \tag{2}$$

Meaning, with a C-rate of 2 the 3.5 ton trucks can potentially charge with a maximum of $80 \cdot 2 = 160$ kW and the 7-20 ton with a maximum of $300 \cdot 2 = 600$ kW. With the SoC from Table 7 the following power usage and charge times could be calculated, as seen if Table 8, with the equation:

$$time\ [h] = \sum \frac{charge\ needed\ [kWh]}{charge\ power\ [kW]} \tag{3}$$

GVW (ton)	Number of trucks	C-rate	Power [kW]	Time [min]
3.5	4	2	160	1,5
3.5	5	2	160	7,1
3.5	15	2 - 1,7	160 - 136	13,1
7-20	5	2	600	1,5
7-20	3	2	600	9
7-20	2	2 - 1,5	600 - 510 - 450	17,5
7-20	1	1,6 - 2 - 0,9	480 - 600 - 270	29,7

Table 8: *Theoretical charge time*

The trucks that has two or more values written in C-rate and power usage start their charging below 10% SoC or end their charge above 60% SoC which follows the charging curve in Figure 10b. Example, for the two 7-20ton trucks that charge between 2-1,5C receives 2C (600kW) from 10% SoC to 60% SoC (150kWh), then 1,7C (510kW) at 60% to 65% SoC (15kWh) and lastly 1,5C (450kW) at 65% to 70% SoC (15kWh). The charge time can thus be calculated with eq 7 as $(\frac{150[kWh]}{600[kW]} + \frac{15[kWh]}{510[kW]} + \frac{15[kWh]}{450[kW]}) * 60 = 17,5min$

However, this is only theoretical values if all trucks follow their maximum allowed C-rate. For the real system a few restrictions are in place. Firstly, the maximum amount of charge the ERS track, the electric road system connected at each charging position, is able to provide is 300kW [16]. Secondly, to not damage the battery the charging time is not allowed to be below 10 minutes [37] [38]. And lastly, the charger is constructed with several isolated DC-DC converters as mentioned, ranging from 25kW to 200kW which gives different power resolutions when divided among the trucks. Wanting to use as few converters as possible to reduce the cost of the system and still be able to achieve a charge time below 30 min the division of converters will differ among the trucks and thus change the charge time between the different cases. The charging time result is presented in Table 9. The table shows the number of trucks at a given weight and their respective energy needed to complete their daily drive. The power in the power column changes depending on which type of DC-DC converter is used in the charger according to the earlier mentioned restrictions. Lastly the charge time is presented which follows the charging curve of Figure 10b.

Three trucks stand out, written in bold in the table, all of which are 7-20 ton. They all consume a lot of energy during the day and even with the maximum allowed charging power they will not complete a daytime charging session in 30 minutes.

25kW dc-dc converter				
GVW (ton)	Number of trucks	To complete day [kWh]	Power [kW]	Time [min]
3.5	4	4	25	9,6
3.5	5	19	50	22,8
3.5	15	34	75	27,2
7-20	5	15	50	18
7-20	3	90	200	27
7-20	**2**	**165**	**300**	**33**
7-20	**1**	**240**	**300-270**	**48**

50kW dc-dc converter				
GVW (ton)	Number of trucks	To complete day [kWh]	Power [kW]	Time [min]
3.5	4	4	25	9,6
3.5	5	19	50	22,8
3.5	15	34	100	20,4
7-20	5	15	50	18
7-20	3	90	200	27
7-20	**2**	**165**	**300**	**33**
7-20	**1**	**240**	**300-270**	**48**

100kW dc-dc converter				
GVW (ton)	Number of trucks	To complete day [kWh]	Power [kW]	Time [min]
3.5	4	4	25	9,6
3.5	5	19	100	11,4
3.5	15	34	100	20,4
7-20	5	15	100	9
7-20	3	90	200	27
7-20	**2**	**165**	**300**	**33**
7-20	**1**	**240**	**300-270**	**48**

150kW dc-dc converter				
GVW (ton)	Number of trucks	To complete day [kWh]	Power [kW]	Time [min]
3.5	4	4	25	9,6
3.5	5	19	100	11,4
3.5	15	34	150-136	13,8
7-20	5	15	100	9
7-20	3	90	300	18
7-20	**2**	**165**	**300**	**33**
7-20	**1**	**240**	**300-270**	**48**

200kW dc-dc converter				
GVW (ton)	Number of trucks	To complete day [kWh]	Power [kW]	Time [min]
3.5	4	4	25	9,6
3.5	5	19	100	11,4
3.5	15	34	160-136	13,8
7-20	5	15	100	9
7-20	3	90	300	18
7-20	**2**	**165**	**300**	**33**
7-20	**1**	**240**	**300-270**	**48**

Table 9: *Charging times depending on which DC-DC converter configuration. Written in bold are the three trucks that is not able to complete their charge in less than 30min due to their high daily energy consumption, regardless of which converter size is used*

3.2 Optimal size of the DC/DC module

To find the optimal size of the DC-DC converter a simulation is used. The simulation investigates three questions.

- Which DC-DC charger can charge the truck fleet the fastest?
- Which charger charges the most individual trucks the fastest?
- Which charger best uses the available power and how does the truck utilize the DC-DC converters while charging?

Simulating for DC-DC converter sizes of 25kW to 200kW and total installed power in the charger system of 1MW to 3MW the number of converters needed for each case is listed in Table 10.

Number of DC-DC converters	1MW	1,5MW	2MW	3MW
25kW	40	60	80	120
50kW	20	30	40	60
100kW	10	15	20	30
150kW	7	10	14	20
200kW	5	8	10	15

Table 10: *Number of DC-DC converters available depending on the total installed power in the charger system*

Simulating for each of the different amounts two times, one with the scenario of longest charge time starts first and one with the scenario of shortest charge time goes first, the resulting charge times are presented in Table 11. The total time is the time it takes for the whole fleet to charge i.e the time when the first truck starts charging to when the last one is finished. Table 11a shows the scenario in which the trucks with the longest charge time starts first and Table 11b shows the scenario in which the trucks with the shortest charge time starts first. The four different time columns of 0.5h, 1h, 1,5h and 2h demonstrate how many trucks finish their charge within the given 30 minute time window if all trucks arrive at the terminal at the same time. It does not mean that a truck that finishes in a later time window than 0.5h charges for more than 30min. In actuality, most trucks complete their daily charge in 30min or less except a few exceptions. Table 12 illustrated those exceptions in how may minutes above 30min that the trucks charge during daytime. It is only the heavier 7-20ton trucks that has a high daily energy consumption that must charge for more than 30min during the day. All the other trucks, especially all the

3.5 ton trucks, only need 30min or less daily charge time at the terminal if there are available converters in the charger system to be connected to their charging position when they arrive at the terminal. The graphs for the best use of the available power can be seen in appendix A. There are more power modules available if the system uses smaller modules and fewer modules available if the system uses larger power modules. When larger power modules are in use a truck which only needs a fraction of the power would still occupy the module for the duration of its charge meaning another truck might have to wait, and a bit of installed power will not be used. For example, a truck needing 25kW will still only use 25kW even if 200kW converters are installed. Meaning 175kW would not be utilized. The graphs in appendix A show this by plotting both the number of DC-DC converters in use and the amount of power drawn from the system at each given time.

Amount of trucks done in given time interval						
Scenario: Longest charge time first						
Installed power	dc-dc converter [kW]	0.5h	1h	1.5h	2h	total time
1MW	25	2	12	14	7	101 min
	50	2	8	15	10	102 min
	100	1	8	18	8	100 min
	150	3	8	15	9	103 min
	200	2	4	6	13	>120 min
1.5MW	25	3	23	9	0	71 min
	50	3	20	12	0	68 min
	100	3	21	11	0	68 min
	150	2	19	14	0	71 min
	200	1	11	22	1	91 min
2MW	25	10	25	0	0	54 min
	50	11	24	0	0	53 min
	100	8	27	0	0	52 min
	150	8	27	0	0	54 min
	200	2	24	9	0	69 min
3MW	25	28	7	0	0	48 min
	50	25	10	0	0	48 min
	100	27	8	0	0	48 min
	150	25	10	0	0	48 min
	200	9	26	0	0	50 min

(a) *Longest charge time first*

Amount of trucks done in given time interval						
Scenario: Shortest charge time first						
Installed power	modules [kW]	0.5h	1h	1.5h	2h	total time
1MW	25	19	11	4	1	115 min
	50	16	13	4	2	114 min
	100	19	10	4	2	117 min
	150	14	15	3	3	107 min
	200	15	10	6	3	>120 min
1.5MW	25	26	8	1	0	86 min
	50	22	11	2	0	87 min
	100	24	8	3		79 min
	150	20	12	2	1	93 min
	200	16	15	3	1	104 min
2MW	25	31	3	1	0	75 min
	50	25	9	1	0	68 min
	100	29	5	1	0	77 min
	150	27	7	1	0	74 min
	200	20	12	2	1	92 min
3MW	25	32	3	0		59 min
	50	32	2	1		69 min
	100	29	6	0	0	58 min
	150	31	3	1	0	65 min
	200	29	5	1	0	66 min

(b) *Shortest charge time first*

Table 11: *Charge time simulation results. The numbers in the table show how many trucks that are done in a given 30Min time window if all trucks arrive at the terminal at the same time*

Longest charge time first: Truck that charge longer than 30min

Total installed power [MW]		1					1,5					2					3				
Converter size [kW]		25	50	100	150	200	25	50	100	150	200	25	50	100	150	200	25	50	100	150	200
Vehicle	Energy Consumption [kWh]																				
Truck 1 : 7-20ton	450	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Truck 2 : 7-20ton	375	3	3	3	3	3	3	3	7	3	3	3	3	3	3	3	3	3	3	3	3
Truck 3 : 7-20ton	375	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Truck 4 : 7-20ton	300								3												

Shortest charge time first: Truck that charge longer than 30min

Total installed power [MW]		1					1,5					2					3				
Converter size [kW]		25	50	100	150	200	25	50	100	150	200	25	50	100	150	200	25	50	100	150	200
Vehicle	Energy Consumption [kWh]																				
Truck 1 : 7-20ton	450	20	17	20	49	5	29	19	18	18	18	18	18	18	32	22	29	18	18	24	21
Truck 2 : 7-20ton	375	15	11	11	3	3	6	8	3	3	3	8	3	6	3	3	3	8	3	3	3
Truck 3 : 7-20ton	375	8	8	3	3		3	7	3	3	3	3	3	3	3	3	3	7	3	3	3
Truck 4 : 7-20ton	300	4		2			3		2			3		2					2		
Truck 5 : 7-20ton	300	3		2																	

Table 12: *Trucks that charge longer than 30min in both cases. The numbers in the table show how many minutes above 30min a truck charges*

3.3 Full scale model and physical dimensions

The DC-DC converters are connected in parallel to the charging positions, which are ERS tracks, and have switches on both the plus and minus output. The switches can be either contactors or semi-conductors such as IGBTs. A contactor can be seen as a proper mechanical switch which when open separates the DC-DC converter side from the charging position side. Having a physical break ensures safety on the charging spots that are not in use since there would be no DC-DC converter connected and thus no current on the ERS side of the contactor. An IGBT however does not ensure this safety. An IGBT is a logical switch constructed from a MOSFET and a BJT which when opened does not create a physical break in the circuit. Thus, if IGBTs are used as switches contactors are still needed at the plus and minus input at each charging position for the system to have a physical break in the circuit when the switches are supposed to be open. This might seem redundant since the system control and monitoring turns off the converters and checks that the current is zero or very low before a switch is to be opened/closed. However, having a physical break in the circuit provides an extra layer of protection which is necessary when working with high currents. IGBTs alone are often also suited for "lower" currents (<30A) compared to contactors and produce a significant amount of heat when switched due to the voltage drop across them. They do however have a high cycle life compared to contactors. [22] In this thesis the contactor is chosen as a switch for the full scale model of the charger system, mainly due to its mentioned isolating properties but also due to the fact that a lower number is needed. However, IGBTs is not neglected as a possible switch and cost calculations and comparison with contactors is done in later sections of this thesis.

With the system being modular, more DC-DC converters and charging positions can be added in parallel to suit the needs of the truck fleet. The number of switches, be it contactors or IGBTs, increase according with the equation:

$$Number\ of\ switches = 2 \cdot 55 \cdot Number\ of\ dcdc\ converters \tag{4}$$

A system using IGBTs as switches also has a few contactors according with the equation:

$$Number\ of\ contactors = 2 \cdot 55 \tag{5}$$

In both equations the number 55 stems from the number of charging positions needed at the Bring terminal which is used as a reference in this thesis. Since Brings truck fleet consists of 55 trucks there needs to be 55 charging spots available on site to allow all to charge during nighttime. That is even though the charger systems total installed power is dimensioned for the 35 trucks that need daytime charging since they consume several MWs more power when charging.

To put into perspective with 55 charging positions and the number of DC-DC converters from Table 10, the number of switches needed will be as illustrated in Table 13.

Number of switches needed				
P_{mod} [kW] \ P_{max}[MW]	1MW	1,5MW	2MW	3MW
25kW	4400	6600	8800	13200
50kW	2200	3300	4400	6600
100kW	1100	1650	2200	3300
150kW	770	1100	1540	2200
200kW	550	880	1100	1650

Table 13: *Number of switches needed in each case of converters size and total installed power*

A charger system build with 25kW converters to a total installed power of 3MW would thus need 13200 switches while a charger system built with 200kW converters to a total installed power of 1MW would need 550 switches. A system using IGBTs would have +110 switches in each case.

To know what magnitude of current a switch should handle flowing through it depends on which size of DC-DC converter is used and what voltage is put over the rails to charge the truck. The current flowing through a switch is thus determined with the equation:

$$I = P/V \tag{6}$$

There I is current P is power and V is voltage. The current with a voltage of 600V and 800V is illustrated in Table 14.

DC-DC converter [kW]	600V	800V
25	41,67 A	31,25 A
50	83,33 A	62,5 A
100	166,67 A	125 A
150	250 A	187,5 A
200	333,33 A	250 A

Table 14: *Switch currents*

For the full scale system, two models are designed for the charger system where it is investigated how the DC-DC converters should be placed as well as how the converters can be connected to the charging positions via the switch matrix. In the models the charging positions are connected to ERS tracks, therefore in the continuing text and figures when ERS tracks is mentioned it is interchangeable with charging positions. In both model versions busbars are used as current carriers with contactors chosen as switches between the busbars. The busbars that carry output current from the DC-DC converters are in the text called DC-DC output busbars and the busbars that carries input current to the ERS tracks are in the text called ERS input busbars. In model version 1, Figure 11, the DC-DC output busbars are vertical to the converter stacks and the ERS input busbars are horizontal. The length of the structure is dependent on the number of DC-DC converters installed in the charger and the width of the structure is dependent on how many ERS tracks as charging spots the charger will provide for. In model version 2, Figure 12, the busbars are turned 90° such that the DC-DC output busbars are horizontal and the ERS input busbars are vertical to the DC-DC converters. Here the length of the structure is dependent on how many charging positions the charger will provide for and the width is dependent on how many DC-DC converters there are in the system. The dimensions for the DC-DC converters in both versions are the same and is sized from the Zekalabs 25kW bidirectional isolated DC-DC converter [39] which in millimeters is (L:420, W:450, H:150) measured in the Elonroad factory. The height of the whole charger structure is also the same in both versions at 2m.

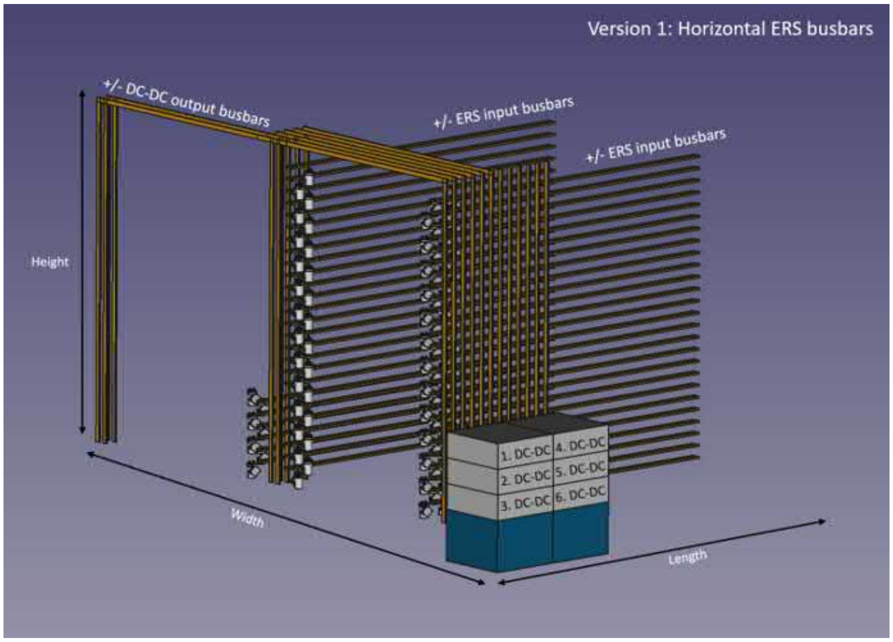


Figure 11: *Version 1: Horizontal ERS input busbars*

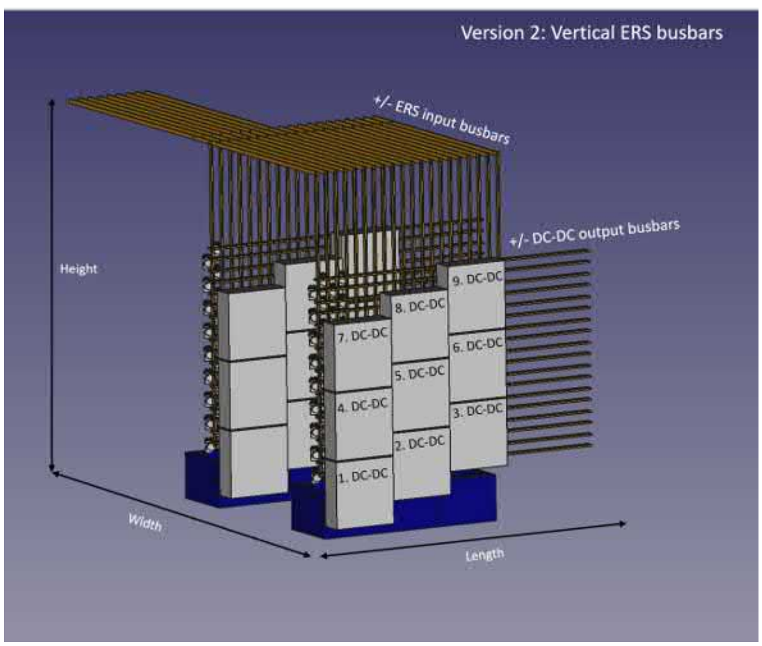


Figure 12: *Version 2: Vertical ERS input busbars*

The blue boxes of the figures are there as a placeholder and as a reference to where the ground plane is located and are not meant to be seen as a part of the models and can therefore be ignored.

3.3.1 Version 1: Horizontal ERS input busbars

Seen from the front view of the charger structure of model version 1, Figure 13, the DC-DC converters are placed in racks stacked three high. The height of the stack is determined by the DC-DC output busbars which require a clearance distance of 60mm between each other and any wall [35]. With each DC-DC converter requiring two DC-DC output busbars to be connected to it, one positive and one negative output, the total number of DC-DC output busbars that can fit within the length of a converter (420mm) is 6 bars. This can be seen in Figure 13 with 1.DC-DC connected to DC-DC output busbar 1, 2.DC-DC connected to DC-DC output busbar 2 etc. Hence the maximum stack is three converters. The total number of stacks in model version 1 can be calculated with the equation:

$$Number\ of\ stacks = \frac{Number\ of\ dcdc\ converters}{3} \tag{7}$$

There the answer of the number of stacks should be rounded up to the closest integer since a stack will still be a stack even if it only contains one or two DC-DC converters. The total length of the charger structure is thus dependent on what size of of DC-DC converters used and the installed power with the equation:

$$Length\ [m] = \frac{420\ [mm] \cdot Number\ of\ stacks}{1000} \tag{8}$$

The result of which is presented in Table 15.

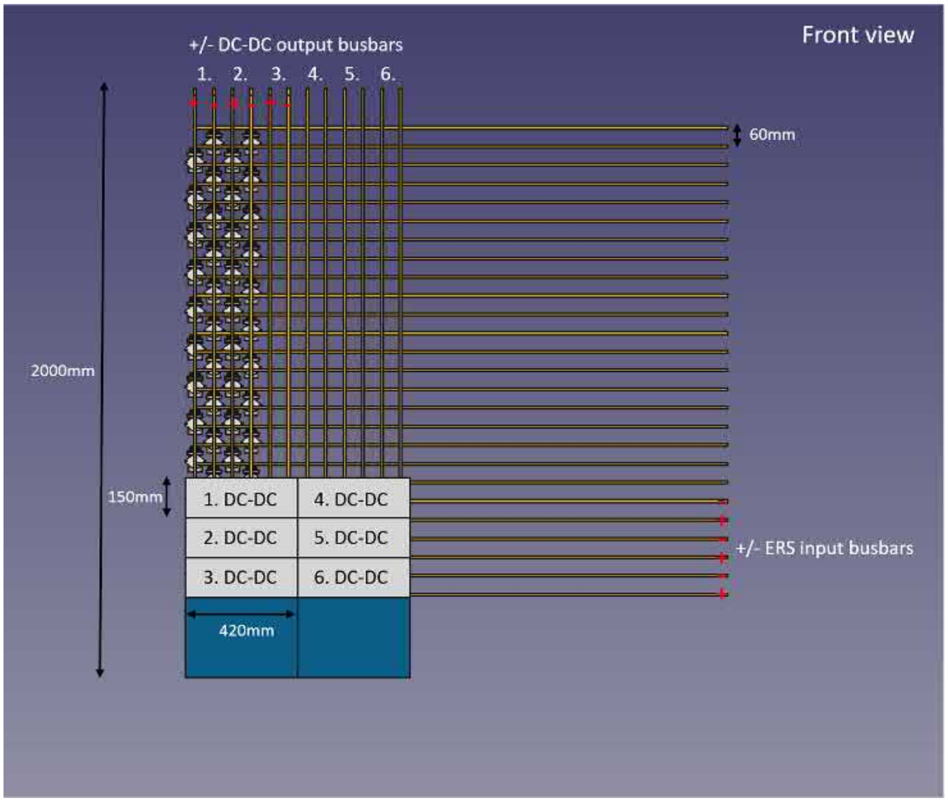


Figure 13: *Version 1: Front view*

Length [m]	1 MW	1,5MW	2MW	3MW
25kW	6,3	9	12,15	18
50kW	3,15	4,5	6,3	9
100kW	1,8	2,25	3,15	4,5
150kW	1,35	1,8	2,25	3,15
200kW	0,9	1,35	1,8	2,25

Table 15: *Charger structure length in meters*

With the height being 2m, a total of 26 ERS input busbars can be fitted on one section of vertical DC-DC output busbars. To support more ERS input busbars without adding more to the height, another section of vertical DC-DC output busbars is added 1,5m behind the first. The converter busbars thus create this "arch" shape seen from the side view of the system in Figure 14. The distance of 1,5m is the minimum allowed working space when working with high currents [35]. The chargers will have these corridors 2m high and 1,5m wide which will allow for easier access to the contactors and busbars behind the converter for assembly and maintenance. Since one DC-DC output busbar arch can fit 26 ERS input busbars on each vertical wall the total width of the charger's structure will depend on how many ERS tracks the charger will be connected to. With a distance of 60mm between any busbars and a busbar width of 10mm the model version 1 width (in meters) can be determined with the equation:

$$Width = (0.06 + 0.01) \cdot 2 \cdot Number\ of\ ERS\ tracks \quad (9)$$

With 55 ERS tracks as charging spots the total number of ERS input busbars are 110 bars, the whole charger structure will be 4,5m wide (the DC-DC output busbars along the roof of the arch will in total be 3m in length but due to the 1,5m clearance distance from the last vertical busbar the whole structure width will be 4,5m).

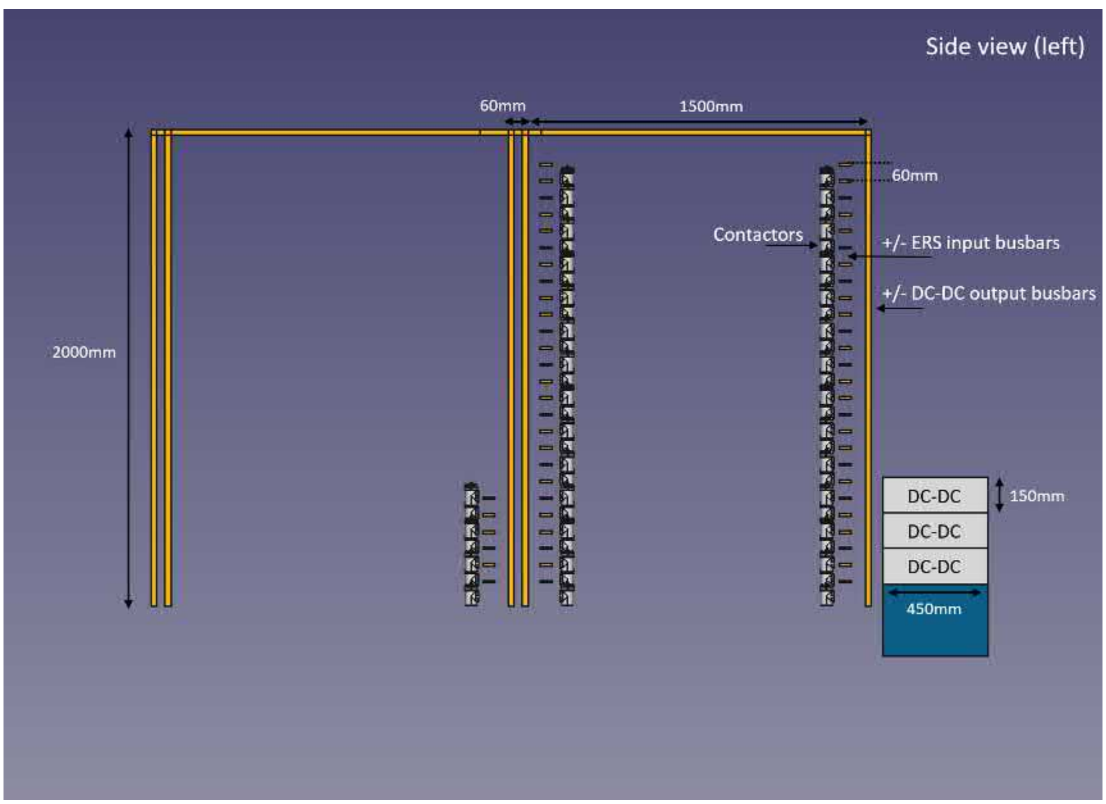


Figure 14: *Version 1: Side view*

3.3.2 Version 2: Vertical ERS input busbars

Seen from the front view of the charger structure of model version 2, Figure 15, the DC-DC converters are placed standing on top of each other three units high, flat on the busbars behind. The diagonal placement of the stacks is to allow each DC-DC converters output terminal to have easier access to their dedicated DC-DC output busbars since the output terminals are located on the short (top) side of the converters. The DC-DC output busbars are in a vertical arrangement where 1.DC-DC is connected to DC-DC output busbar 1, 2.DC-DC is connected to DC-DC output busbar 2 etc. In this arrangement a 3x3 grid is chosen as a suitable configuration to build the stacks within the height of the whole charger structure of 2m. Thus, if more converters are to be added a new section of vertical DC-DC output busbars is added which can be seen in the side view of the structure, Figure 16. The width of the charger structure is therefore dependent on the number of converters in the system. With a clearance distance of 1,5m between the sections the total width becomes that of Table 16. The length of the structure is dependent on the number of ERS input busbars i.e the number of charging spots connected to ERS tracks the charger should provide for. With a clearing distance of 60mm between any busbars and a busbar width of 10mm the length (in meters) is calculated with the equation:

$$Length = (0.06 + 0.01) \cdot 2 \cdot Number\ of\ ERS\ tracks \tag{10}$$

For the terminal with 55 charging spots connected to ERS tracks the length of the charging structure is 7,7 meters.

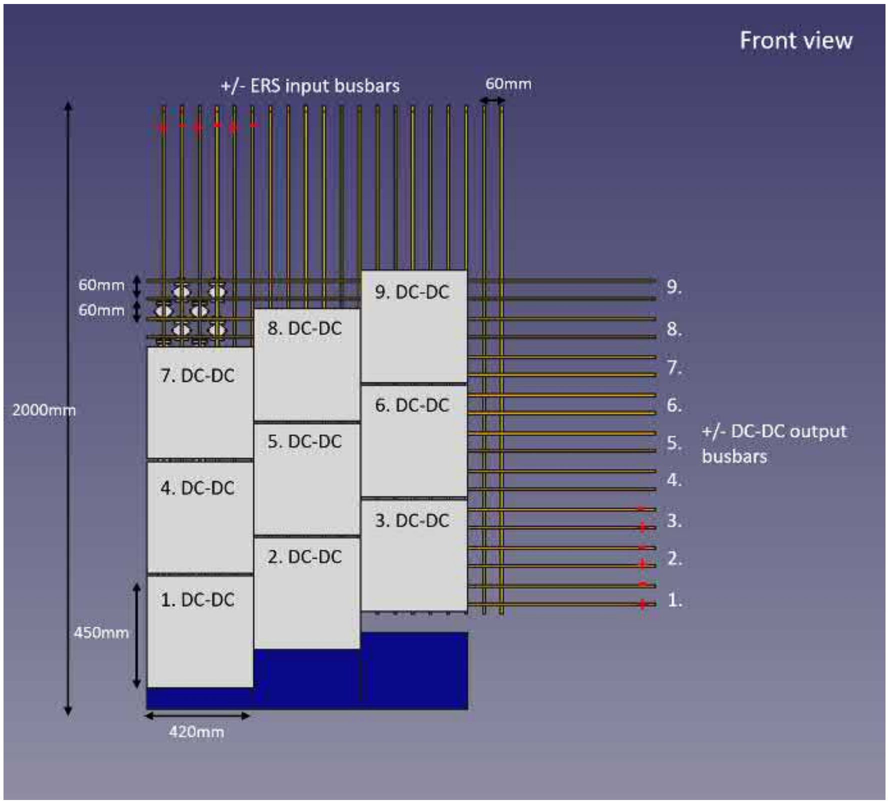


Figure 15: *Version 2: Front view*

Version 2 has similar "arch" structures, visible in Figure 16, only that in version 2 they are made up of the vertical ERS input busbars. This version will also have these long maintenance corridors 1,5m wide and 2m high to allow easy access to the contactors behind the converters and the DC-DC converters of each section.

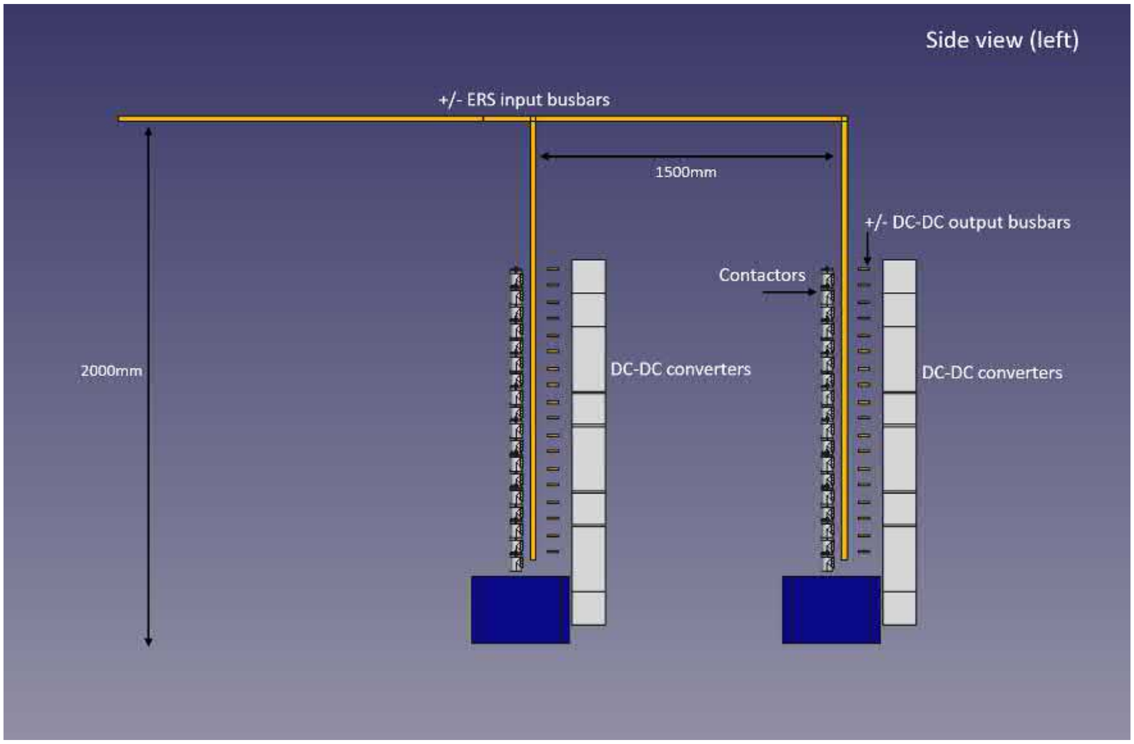


Figure 16: *Version 2: Side view*

Width [m]	1 MW	1,5MW	2MW	3MW
25kW	7,5	10,5	13,5	21
50kW	4,5	6	7,5	10,5
100kW	3	3	4,5	6
150kW	1,5	3	3	4,5
200kW	1,5	1,5	3	3

Table 16: *Charger structure width in meters*

3.3.3 Contactor connection

The contactor connection between the DC-DC output busbars and ERS input busbar is the same in both versions except which busbars are vertical or horizontal. How the connection works is illustrated in Figure 17. The contactors works in pairs of minus and plus charge to connect one DC-DC converter (a pair of +/- bubsars) with one ERS track (another pair of +/- busbars).

Such a pair can be seen in Figure 17 as Switch 1 and 2. The many pairs of contactors form a matrix seen in Figure 18. The matrix should be seen having rows and columns where each row contains a pair of horizontal busbars and each column contains a pair of vertical busbars. Thus, all pairs of contactors along one row of the matrix all connect the same horizontal pair of busbars to all pairs of vertical busbars of every column. Vice versa with all pairs of contactors along a column connect the same pair of vertical busbars to all pairs of horizontal busbars. With this configuration every pair of vertical bars can be connected to every pair of horizontal bars, i.e allowing the system to connect an arbitrary number of DC-DC converters to any ERS track by adding more DC-DC output busbars pairs along a single pair ERS input busbar.

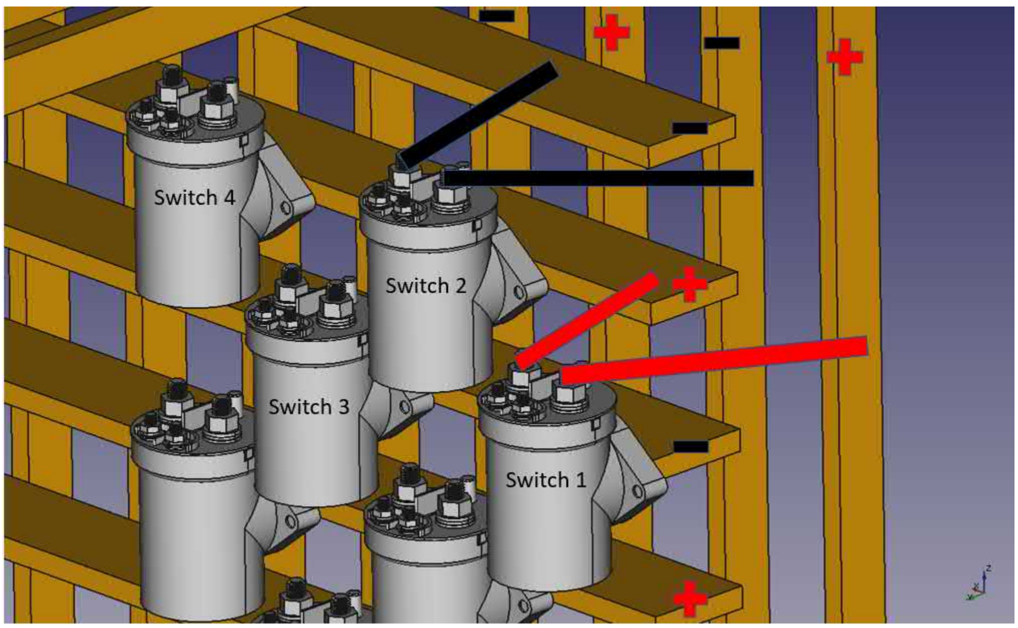


Figure 17: *Switch connection pairs*

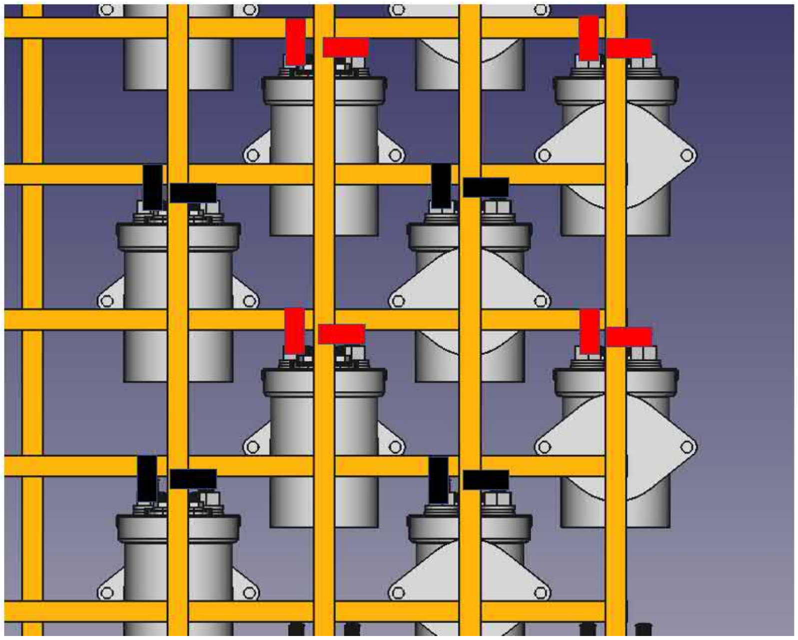


Figure 18: *The switch matrix*

3.4 Components, materials and their costs

The cost is based on the market price of the components and the currency is in euro €. If a component has been picked from a store using a different currency such as USD [$] or SEK [kr] the exchange rate is from 2021-04-12 and is 1kr = 0.097 € and 1$ = 0.92 €. [20]

In the following subsections the cost calculations for the DC-DC converters, contactors, IGBTs and busbars are presented with graphs of the total cost for the two charger models presented in the end.

3.4.1 DC-DC converters

The cost of the isolated DC-DC converters is approximated using the production volume cost of 100 units/year together with two known volume market prices, purchased by Elonroad. The known market prices are for a 25kW isolated bidirectional DC-DC converter and a 200kW isolated bidirectional DC-DC converter and are 2500€ [31] and 9600€ [13] respectively. The production cost of 100 units/year in €/kW is shown in Table 17 and follows the graph of Figure 19 [14].

kW	€/kW
25	75,7
50	36,2
100	25,4
150	20,4
200	20

Table 17: *Production cost of isolated DC-DC converters in kW/€*

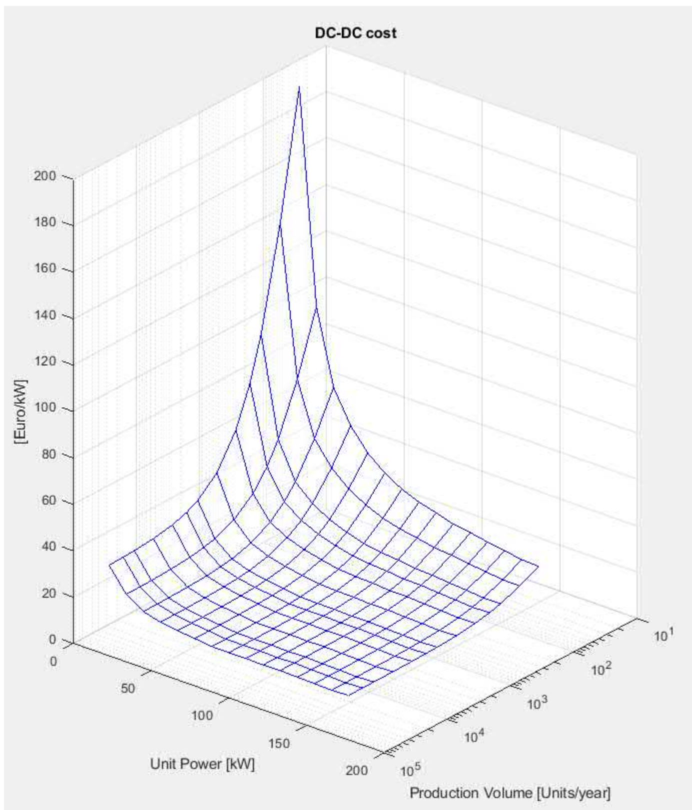


Figure 19: *DC-DC converter cost in kW/€depending on unit power and production volume*

Calculating the production cost for each of the modules and then calculating the increase in price for the known converters, an increase for the unknown converters is approximated with the average of the two known increases. The approximated market prices for one DC-DC converter of each size is as listed in Table 18

Converter size [kW]	Production cost [€]	increase	Market price [€]
25kW	1892,5	1,32	2500*
50kW	1810	1,86	3367,5
100kW	2540	1,86	4726,7
150kW	3060	1,86	5693
200kW	4000	2,4	9600*

Table 18: *Approximated cost of isolated DC-DC converters (*known prices)*

With the approximated cost together with the number of converters depending on the installed power, Table 10, the total cost for the DC-DC converters can be calculated for each type of converter and installed power. Table 19 shows the total cost.

Cost [kEUR]	1MW	1,5MW	2MW	3MW
25kW	100	150	200	300
50kW	67,4	101	134,7	202,1
100kW	47,3	70,9	94,5	141,8
150kW	39,9	56,9	79,7	113,9
200kW	48	76,8	96	144

Table 19: *Cost of isolated DC-DC converters for the charger system depending on which converter size and total installed power*

3.4.2 Contactors

The investigated contactors and their respective costs are shown in Table 20.

Manufacturer	Product	Current rating [A]	€
TE connectivity	LEV200 [28]	500	103,5
TE connectivity	LEV100 [27]	100	103,5
TE connectivity	IHV200 [24]	250	143,5
TE connectivity	IHV50 [25]	50	85
Altran Magnetics	ALEV200-C [7]	200	36

Table 20: *Different contactors*

Depending on what type DC-DC converter is chosen for the system the current will differ as mentioned in Table 14. Different contactors can thus be used according to their current rating. In this thesis the LEV200 for converter size 150kW and 200kW and ALEV200 for converter size 25kW, 50kW and 100kW are chosen. Multiplying the cost of the chosen contactors with the number of switches needed in each case of converters size and installed power gives the total cost of converters for the charger, Table 21.

Cost [kEUR]	1MW	1,5MW	2MW	3MW
25kW	160	240	320	480
50kW	80	120	160	240
100kW	40	60	80	120
150kW	77	110	155	221
200kW	55	88	110	166

Table 21: *Contactor cost depending on converter size used and installed power of the charger*

3.4.3 IGBTs

The investigated IGBTs and their respective cost are shown in Table 22. Presented in the table is the manufacturer, product and if the IGBT is in a single or modular configuration. The current rating is shown at a specified temperature. In the same column the voltage rating is also present. Lastly, the last column shows the price of the IGBT at a high unit purchase of above 500 units.

Manufacturer	Product	Type	Current and voltage rating [A]/[V]	€
IXYS	IXYS140 [26]	Single	480 (140 at 110°) / 1200	29
Infineon	FD200 [17]	Module	200 at 65°/ 1200	138
Infineon	FD300 [18]	Module	300 at 60°/ 1200	164
Infineon	FZ400 [21]	Module	400 at 100°/ 1200	119
Infineon	FD450 [19]	Module	450 at 75°/ 1200	152

Table 22: *Different IGBTs and their cost*

The IGBTs chosen for the calculations in this thesis is the IXYS140. For the contactors, where $2 \cdot ERS\ tracks$ is needed, the LEV200 was chosen as it has the highest current rating making it suitable to carry the current able to provide 300kW to an ERS rail.

Table 23 shows the total cost for the IGBTs plus the contactors in a system with 55 ERS tracks as charging spots.

Cost [kEUR]	1MW	1,5MW	2MW	3MW
25kW	138	202	266	393
50kW	75	107	138	202

Table 23: *The cost of IGBTs + contactors*

3.4.4 Busbars

The busbars can be either made with copper, Cu or aluminium, Al. The chosen cost of the metals is the market price on the 2020-04-14 and is for Cu: 10,24€/kg [12] and for Al: 3,25 €/kg [8]. The size of the busbars is determined from the busbars current carrying capacity. For copper the rating is determined with the equation [10]:

$$Current\,[A] = 1,2 \cdot cross\,sectional\,area\,[mm^2] \tag{11}$$

And for aluminuim the rating is determined with the equation [10]:

$$Current\,[A] = 0,8 \cdot cross\,sectional\,area\,[mm^2] \tag{12}$$

In the equations the constants 1,2 (for copper) and 0,8 (for aluminium) is the material constant of how much amperes per square mm the material can withstand. [10]

For this thesis a current carrying capacity of 500A is chosen and the cross-sectional areas for the different metals is calculated from eq 14 and eq 15 to be $Cu_{csa} = 420mm^2 = 0,00042m^2$ and $Al_{csa} = 625mm^2 = 0,000625m^2$. 500A is chosen because it allows the ERS input busbars to be able to handle a scenario were 300kW is to be outputted from an ERS track in a 600V system: $\frac{300\,[kW]}{600\,[V]} = 500\,[A]$ and it is well within the margin of a 800V system: $\frac{300\,[kW]}{800\,[V]} = 375\,[A]$.

The total volume needed of each metal is then determined with the equation:

$$Volume\,[m^3] = cross\,sectional\,area\,[m^2] \cdot length[m] \tag{13}$$

There the length is the total length of the busbars in the charger structure.

The complete mass of the metals needed in the structure is then determined by multiplying the total volume, from eq 16, with the density of the metals.

$$Mass\,[kg] = \rho \cdot volume\,[m^3] \tag{14}$$

Where the density for the different metals is $\rho_{Cu} = 8960 kg/m^3$ and $\rho_{Al} = 2710 kg/m^3$.

The cost, in €, is then calculated by multiplying the mass from equation eq 17 with the cost for each metal.

$$Cost_{Cu} = 10,24 \cdot Mass_{Cu} \tag{15}$$

$$Cost_{Al} = 3,25 \cdot Mass_{Al} \tag{16}$$

Version 1: Horizontal ERS input busbars

Depending on what model is used the cost will differ due to their different sizes. For the version 1 model with 55 ERS tracks as charging spots one DC-DC converter requires 10 vertical busbars each 2m in length and 2 horizontal busbars 3,1m in length. The total length of busbars for one module is thus 26,2m. Together with the number of converters available for each type of converter and installed power of the charger, Table 10, the total length of the busbars in the charger structure becomes that of Table 24.

Length [m]	1 MW	1,5MW	2MW	3MW
25kW	1741	2562	3432,5	5124
50kW	870,5	1281	1741	2562
100kW	460	640,5	870,5	1281
150kW	331,9	460	614,3	870,5
200kW	230	358,1	460	640,5

Table 24: *Total length of the busbars in version 1 with 55 charging spots*

For copper, with the volume calculated from eq 13 and mass calculated from eq 14, the cost of the busbars for each converter size and installed power is calculated with eq 14 and can be seen in Table 25.

Cu cost [kEUR]	1 MW	1,5MW	2MW	3MW
25kW	67,1	98,7	132,3	197,5
50kW	33,5	49,4	67,1	98,7
100kW	17,7	24,7	33,5	49,4
150kW	12,8	17,7	23,7	33,5
200kW	8,9	13,8	17,7	14,7

Table 25: *Total cost for copper busbars in version 1 with 55 charging spots*

For aluminium, with the volume calculated from eq 13 and mass calculated from eq 14, the cost of the busbars for each converter size and installed power is calculated with eq 16 and can be seen in Table 26.

Al cost [kEUR]	1 MW	1,5MW	2MW	3MW
25kW	9,6	14,1	18,9	28,2
50kW	4,8	7,1	9,6	14,1
100kW	2,5	3,5	4,8	7,1
150kW	1,8	2,5	3,4	4,8
200kW	1,2	2	2,5	3,5

Table 26: *Total cost for aluminium busbars in version 1 with 55 charging spots*

Version 2: Vertical ERS input busbars

For the version 2 model with 55 charging spots a single DC-DC converter needs two horizontal output busbars 7,7m each. For the ERS input busbars there are 110 vertical bars needed each 2m, two bars for each ERS track as well as 110 horizontal bars connecting each section in the charger structure. The length of the horizontal bars are therefore dependent on the number of converters for each converter size and installed power from 10. The total length of the busbars in the charger structure thus becomes that of Table 27.

Length [m]	1 MW	1,5MW	2MW	3MW
25kW	2400	3490	2580	7145
50kW	1310	1855	2400	3490
100kW	765	845	1310	1855
150kW	332	765	829	1310
200kW	300	348	765	845

Table 27: *Total length of the busbars in version 1 with 55 charging spots*

For copper, with the volume calculated from eq 13 and mass calculated from eq 14, the cost of the busbars for each converter size and installed power is calculated with eq 15 and can be seen in Table 28.

Cu cost [kEUR]	1 MW	1,5MW	2MW	3MW
25kW	91,6	133,1	174,6	272,6
50kW	50	70,8	91,6	133,1
100kW	29,2	32,2	50	70,8
150kW	12,6	29,2	31,6	50
200kW	11,4	13,2	29,2	32,2

Table 28: *Total cost for copper busbars in version 2 with 55 charging spots*

For aluminium, with the volume calculated from eq 13 and mass calculated from eq 14, the cost of the busbars for each converter size and installed power is calculated with eq 16 and can be seen in Table 29.

Al cost [kEUR]	1 MW	1,5MW	2MW	3MW
25kW	13,1	19	24,9	38,9
50kW	7,1	10,1	13,1	19
100kW	4,2	4,6	7,1	10,1
150kW	1,8	4,2	4,5	7,1
200kW	1,6	1,9	4,2	4,6

Table 29: *Total cost for aluminium busbars in version 2 with 55 charging spots*

3.4.5 Total costs of the two switch matrix charger models

Below is the total cost of the charger system for 55 charging spots and busbars with a current carrying capacity of 500A from the individual costs of the components from the previous subsections. The total cost varies from system to system depending on if the busbars are made with copper or aluminium and if contactors or IGBTs are used as switches. Each graph shows the cost for each converter size used and total installed power in the charger. The four groups of stacks (left to right) represent the total installed power of 1MW, 1.5MW, 2MW and 3MW there the five stacks in each group (left to right) represent which converter size is used from 25kW, 50kW, 100kW, 150kW to 200kW. Figure 20 to Figure 23 shows the total cost for model version 1 and Figure 24 to Figure 27 shows the total cost of model version 2. The y-axis in all figures is in thousand euros.

Model version 1

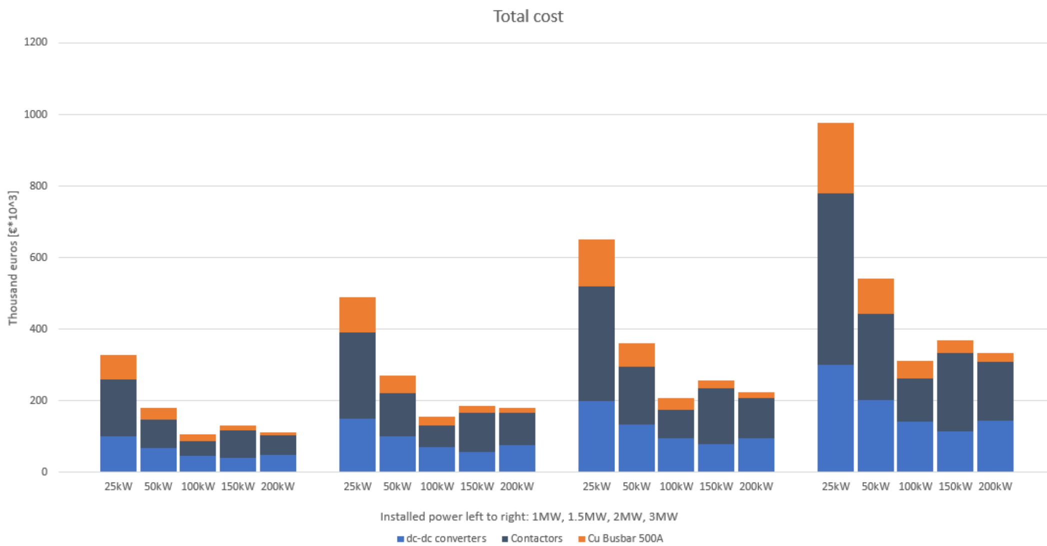


Figure 20: *Total cost of the model version 1 charger with Cu busbars and contactors as switches*

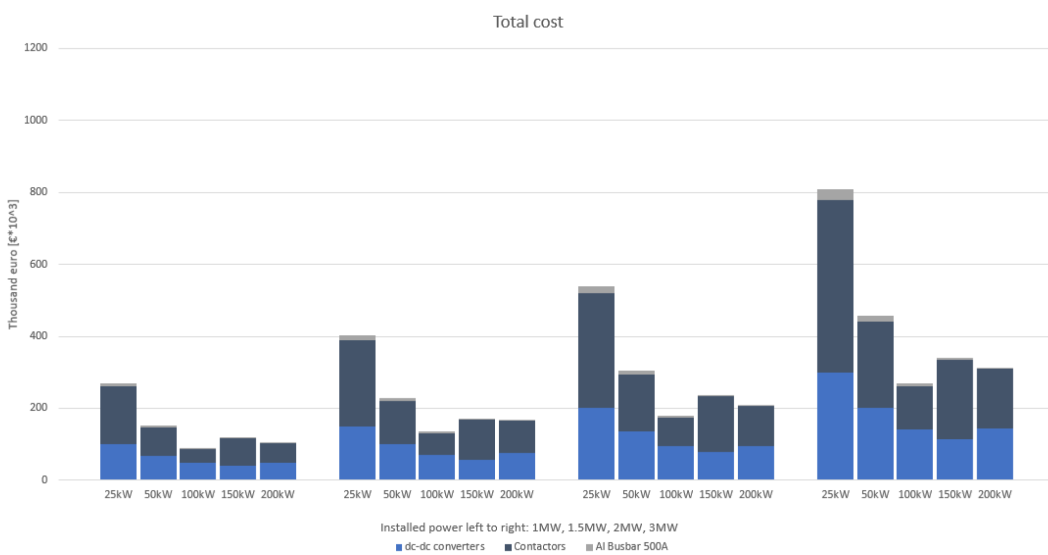


Figure 21: *Total cost of the model version 1 charger with Al busbars and contactors as switches*

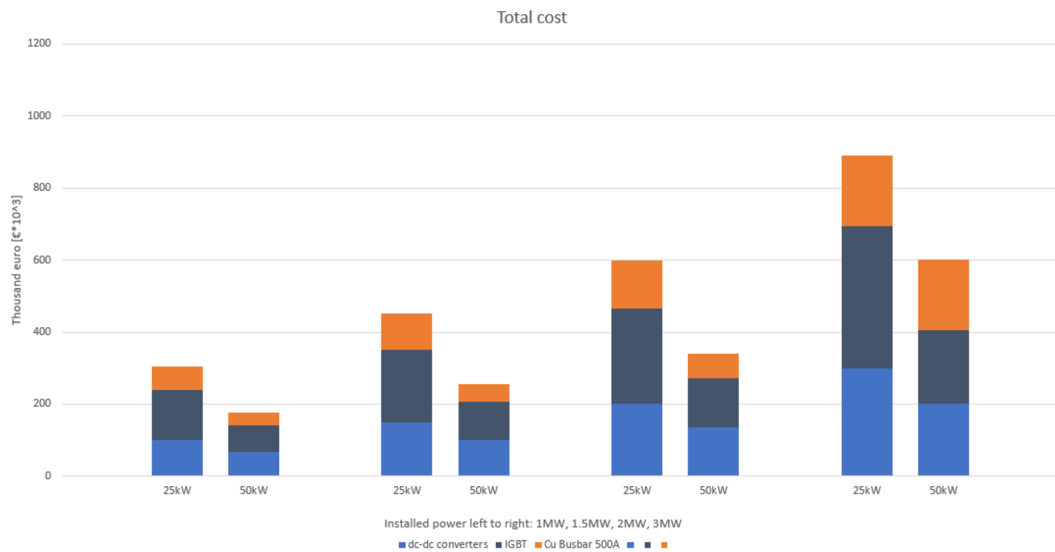


Figure 22: *Total cost of the model version 1 charger with Cu busbars and IGBTs as switches*

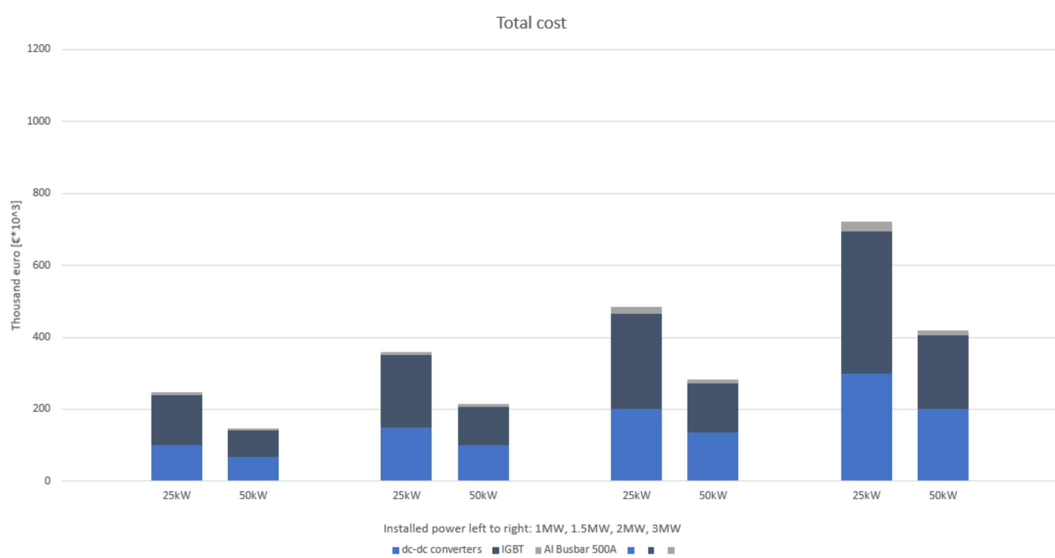


Figure 23: *Total cost of the model version 1 charger with Al busbars and IGBTs as switches*

Model version 2

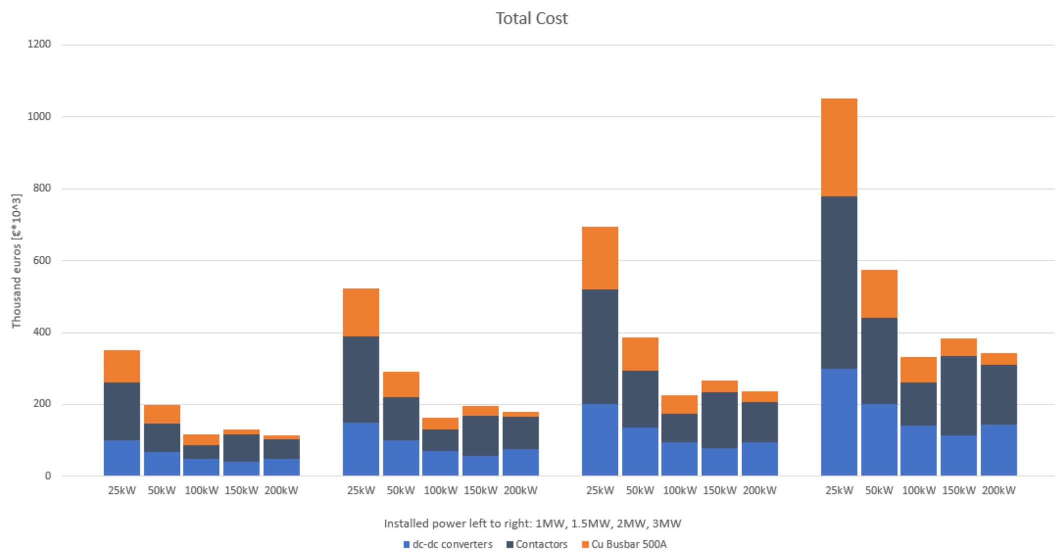


Figure 24: *Total cost of the model version 2 charger with Cu busbars and contactors as switches*

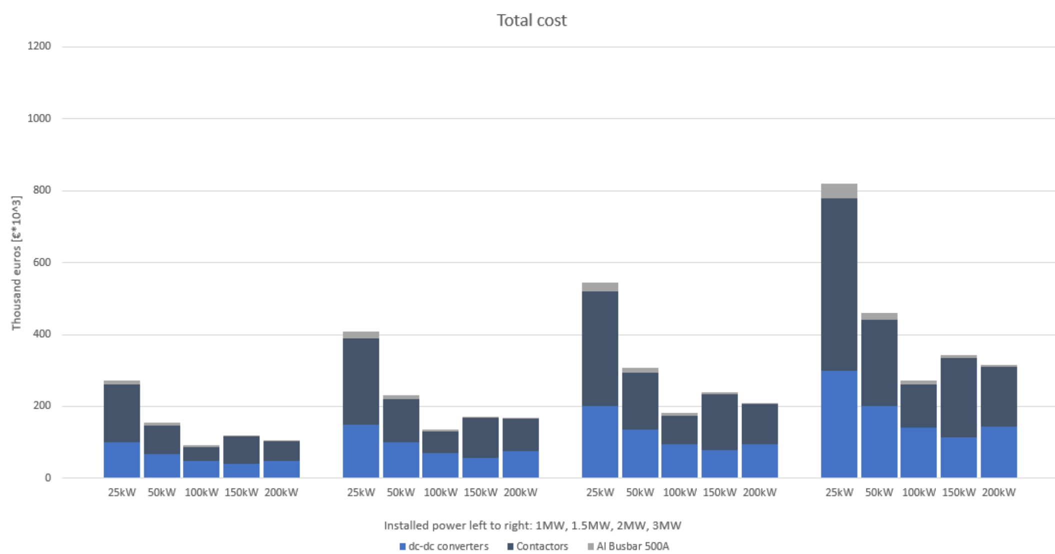


Figure 25: *Total cost of the model version 2 charger with Al busbars and contactors as switches*

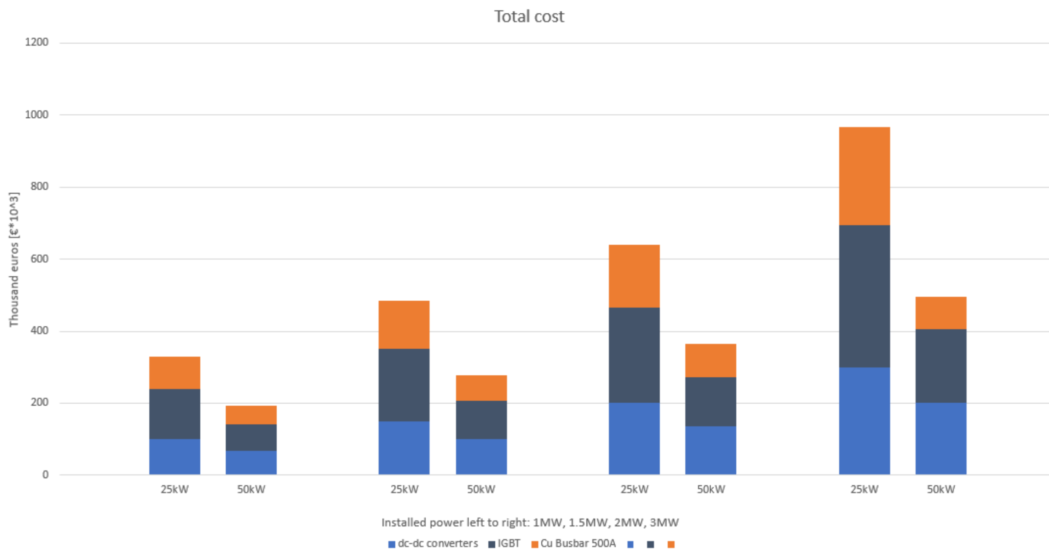


Figure 26: *Total cost of the model version 2 charger with Cu busbars and IGBTs as switches*

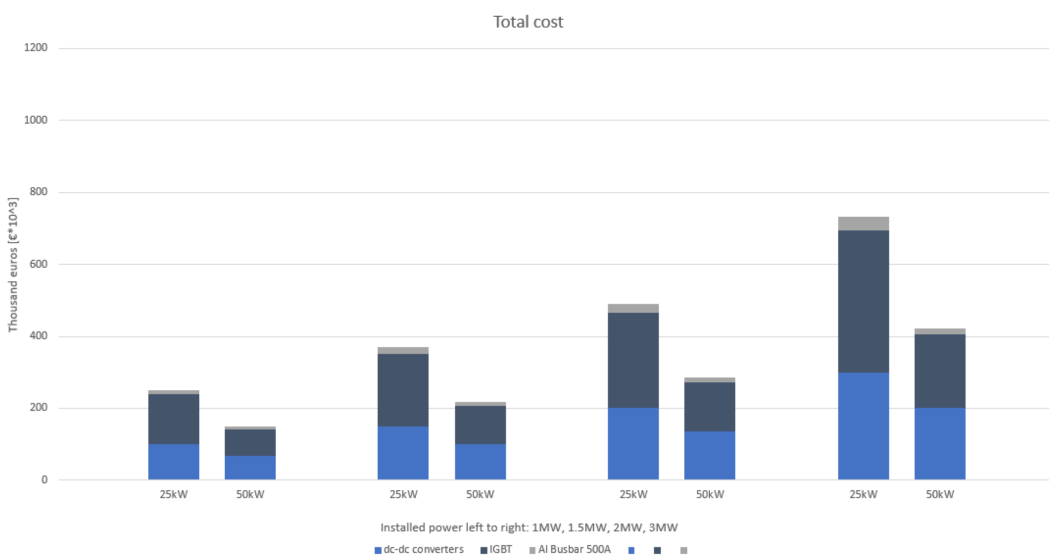


Figure 27: *Total cost of the model version 2 charger with Al busbars and IGBTs as switches*

3.5 A conventional charger model comparison

3.5.1 55 full power charging positions

The switch matrix charger offers flexibility of having any charging spot become a fast charger by switching more DC-DC converters to that particular ERS track connected as a charging spot. With that approach a truck can stand at any ERS track and receive the charge power it needs. A more conventional approach to a charger, while still having the same flexibility in the system, would be to have a fast charger at every charging spot. The number of DC-DC converters needed in such a system is determined with the equation:

$$\#\,of\,DC-DC\,converters = \#\,of\,charging\,spots \cdot \frac{Converter\,size}{Rated\,charging\,spot\,power} \tag{17}$$

Table 30 shows the number of DC-DC converters for a terminal with 55 charging spots having 350kW rated fast chargers at each charging position constructed with converters ranging in size from 25kW to 150kW. 350kW rated fast chargers as that is as of today the latest gen-3 fast charging stations available [4] [23]. The table also shows the total cost for each number of converters using the prices for converters from Table 17.

DC-DC converters	Number of converters	Cost [kEUR]
25kW	770	1925
50kW	385	1296,5
100kW	192,5	909,7
150kW	128,3	730,6

Table 30: *Number of DC-DC converters and cost of fast chargers at every charging spot*

Since every ERS track will be connected to a fast charger no switch matrix is needed. However, a couple of switches are still needed to be able to connect and disconnect each charging position with its designated conventional fast charger as in Figure 28.

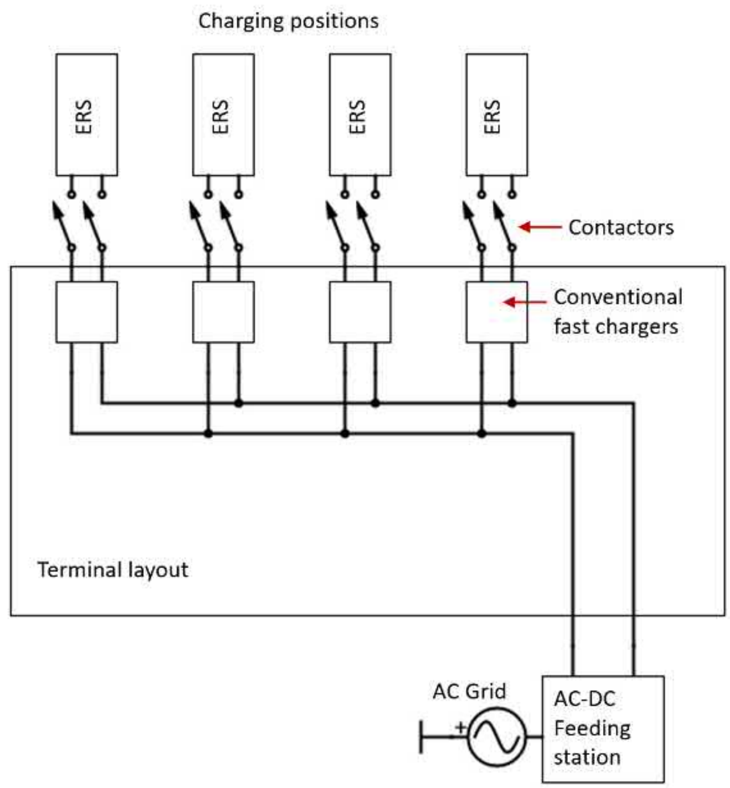


Figure 28: *Conventional fast charger connection*

For 55 ERS tracks as charging positions and using the LEV200 contactor, Table 20, the total cost of the switches is 11,04kEUR .

3.5.2 Dedicated night charging positions

Having all trucks fast charge at the terminal is improbable [34]. In actuality due to the truck's daily routes only about 8-10 of the 55 trucks will use the terminal as a charging station. It is only at night that all the trucks will charge at the terminal and that charging is done with a much lower power. To still have a flexible system for the trucks that need daytime charging 10 charging spots are designated to 350kW rated fast chargers, built with converters ranging in size from 25kW to 150kW. The remaining 45 charging spots can be used for night charging using either a 25kW converter or a 50kW converter. The number and cost of converters is thus significantly reduced. Using eq 20 the number of converters and cost for the fast chargers is calculated, the result of which is presented in Table 31. The cost for the night chargers using either 25kW or 50kW is presented in Table 32.

DC-DC converters	Number of converters	Cost [kEUR]
25kW	140	350
50kW	70	235,7
100kW	35	165,4
150kW	24	136,6

Table 31: *Number of DC-DC converters and cost of fast chargers at 10 charging spots*

DC-DC converters	Number of converters	Cost [kEUR]
25kW	45	112,5
50kW	45	151,5

Table 32: *Cost of DC-DC converters used for night charging*

The number of switches is still only dependent on the number of charging spots. However for the spots only meant for night charging the ALEV200 contactor, Table 20, can be used. The total cost of contactors is then 5,28kEUR.

The only busbars needed in the charger is between the DC-DC converters and the AC-DC feeding station, i.e the transformer located at the terminal. Since no switch matrix is present there will not be a cage like structure of busbars connecting every converter with every ERS rail. The cost of the busbars in the conventional chargers is therefore highly dependent on the layout of the terminal the charger is implemented on. With everything from where the transformer is located on the premises to where the charging spots are placed. Using the Bring logistics terminal as a reference, its layout can be seen in Figure 29 [34].

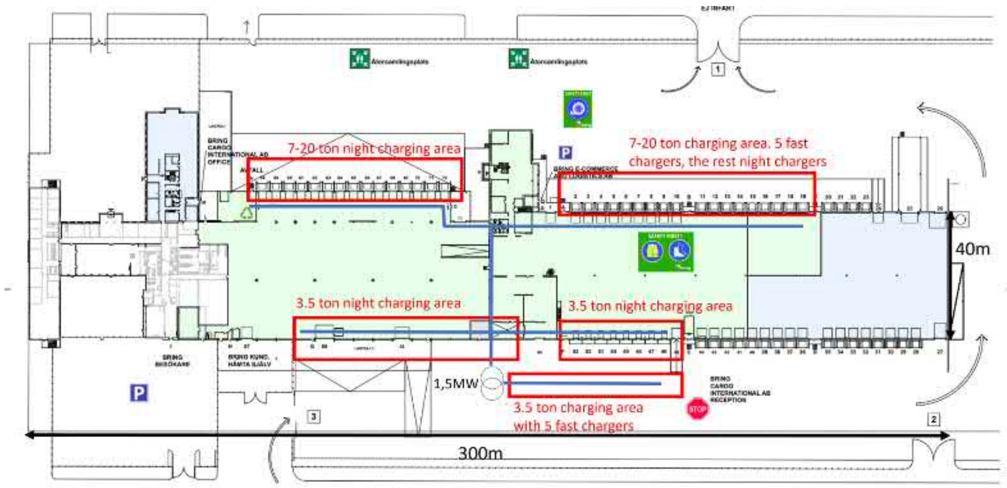


Figure 29: *Bring logistics terminal layout with potential charging spots*

At the terminal there is a 1,5MW transformer present. Close to it are potential charging spots for the 3.5ton trucks to charge both during the day and during the night. On the other side of the building there are potential charging spots for the 7-20ton trucks. Connecting these areas with the transformer, the busbar length would approximately be 370m, seen as the blue lines in the figure, and the current carrying capacity would be 1875A (eq 6). Depending on which metal is used the cross-sectional area will differ as well as the cost. If the busbar is made out of copper the cross-sectional area is $1560mm^2$2 (eq 11) which brings the cost to about 53kEUR (eq 15). If the busbar is made of aluminium the cross-sectional area is $2304mm^2$ (eq 12) which bring the cost to about 7,64kEUR (eq 16).

3.5.3 Total cost of the two conventional charger systems

Below is the total cost of the conventional charger implemented at the Bring terminal in Malmö presented. Figure 30 and Figure 31 shows the total cost if all of the 55 charging spots has their own 350kW fast charger with either busbars made out of copper or aluminium. Whereas the next four figures show the total cost if only 10 charging spots have access to a fast charger and the rest only has a single converter of either 25kW or 50kW for night charging. Figure 32 and Figure 33 shows fast chargers built with 25kW converters and busbars made out of either copper or aluminium. Figure 34 and Figure 35 shows fast chargers built with 50kW converters and busbars made out of either copper or aluminium. The y-axis in all figures is in thousand euros.

55 full power charging positions

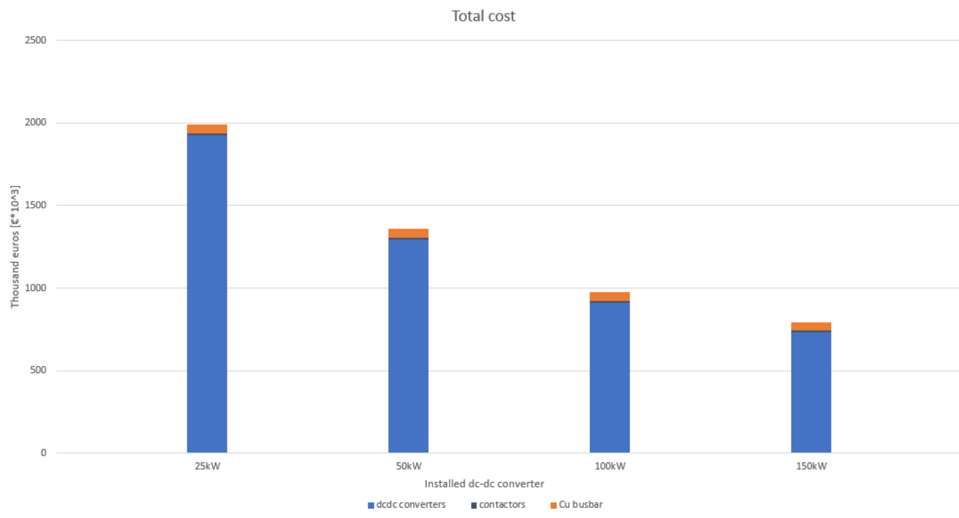


Figure 30: *350kW fast charger at every charging spot built with the corresponding converters. The busbars are made out of copper*

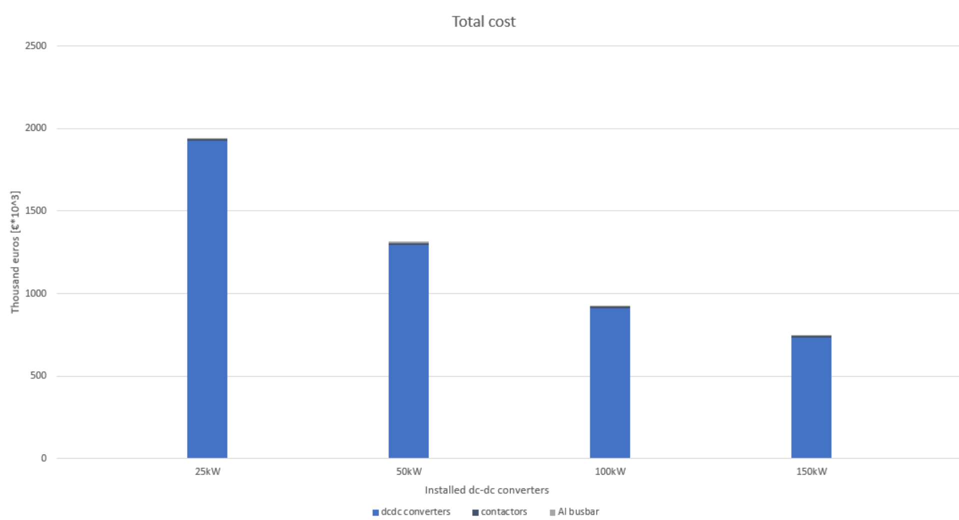


Figure 31: *350kW fast charger at every charging spot built with the corresponding converters. The busbars are made out of aluminium*

Dedicated night charging positions

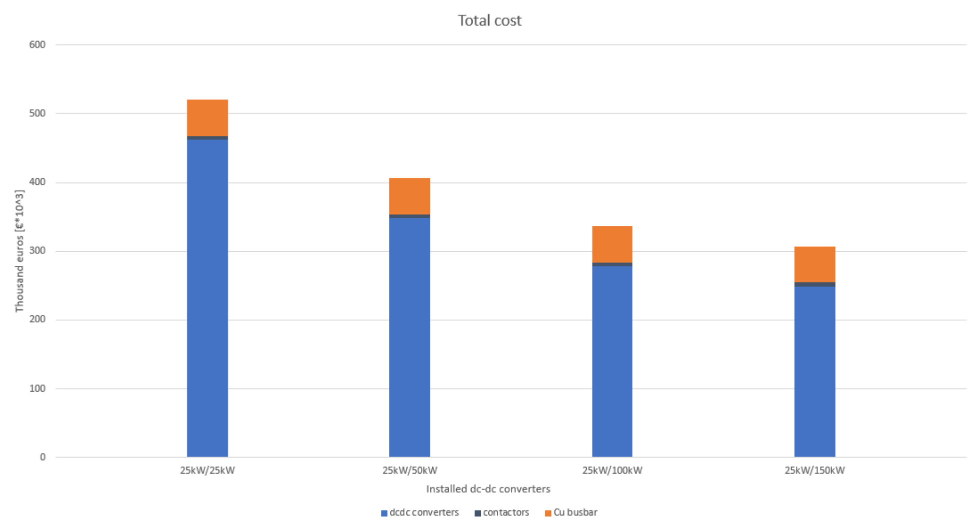


Figure 32: *350kW fast charger at 10 charging spots. Night chargers uses 25kW converters. The busbars are made out of copper*

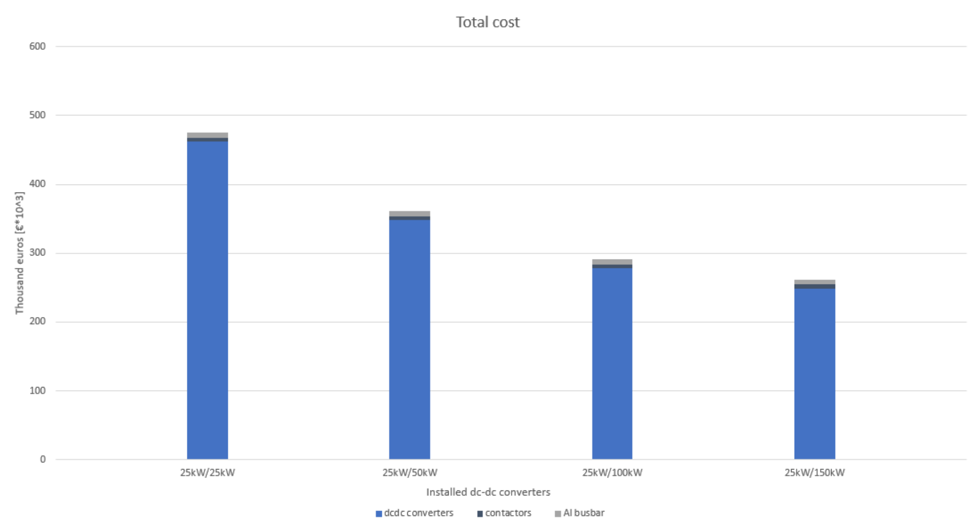


Figure 33: *350kW fast charger at 10 charging spots. Night chargers uses 25kW converters. The busbars are made out of aluminium*

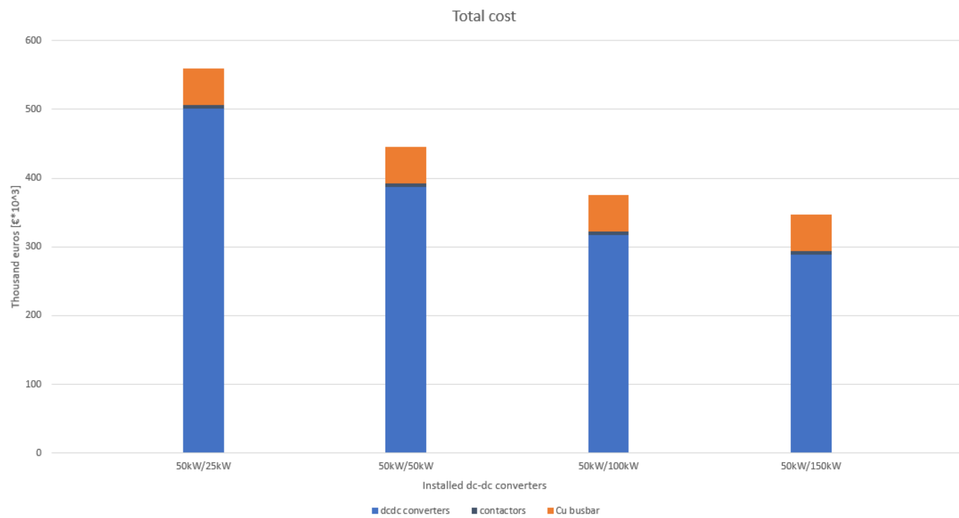


Figure 34: *350kW fast charger at 10 charging spots. Night chargers uses 50kW converters. The busbars are made out of copper*

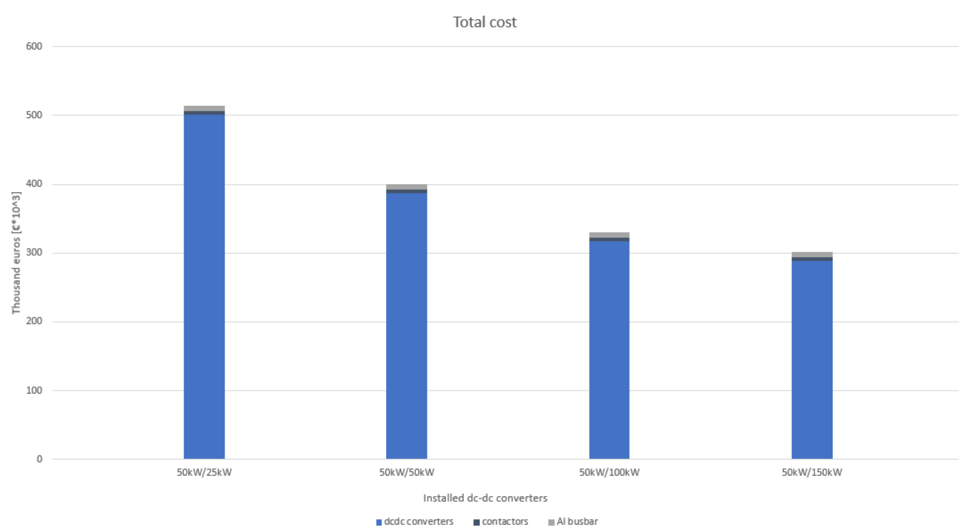


Figure 35: *350kW fast charger at 10 charging spots. Night chargers uses 50kW converters. The busbars are made out of aluminium*

3.5.4 Robustness of the system

Another comparison made with a conventional charger system is the robustness, specifically the availability of chargers. A small example would be having a charging area with 3 charging poles each connected to a 150kW (3x50kW) charging station able to facilitate three electric vehicles. If one of the chargers broke and three vehicles want to charge at the same time one must wait while the other two charges. In a switch matrix charger however, the converters can be rerouted between the charging spots. Thus, allowing all charging spots to function, but with a lower output such that instead of one vehicle needing to wait a long time for a spot to be free, all can charge but with a slightly longer charge time. Calculating for a vehicle with 80kWh battery with the same charging curve as Figure 10b and a need to charge from 10% SoC to 80% SoC the charging time can be calculated with eq 3 to be approximately 35min using the chargers from the example. The same charging time applies for a switch matrix charger with the same number of converters. With the conventional charger if one charger is broken the waiting time for one vehicle becomes at a maximum 35min extra if the other charging spots are occupied. With the switch matrix the converters can be rerouted from being 3x50kW at two charging spots to 2x50kW at three charging spots. Now the charge time is instead 38min for each vehicle and no one must wait.

4 Small scale prototype

To test and verify the switch matrix as a working solution a small scale prototype was constructed prove that the switch matrix was feasible to build and to control. The prototype follows the circuits of Figure 36 and Figure 37, where the latter is the circuit for the contactor control. Switch 1-8 and S1-S8 in the figures represents the contactors and can be interpreted as interchangeable between the figures. In the following subsections S1-S8 will be used when talked about the contactors.

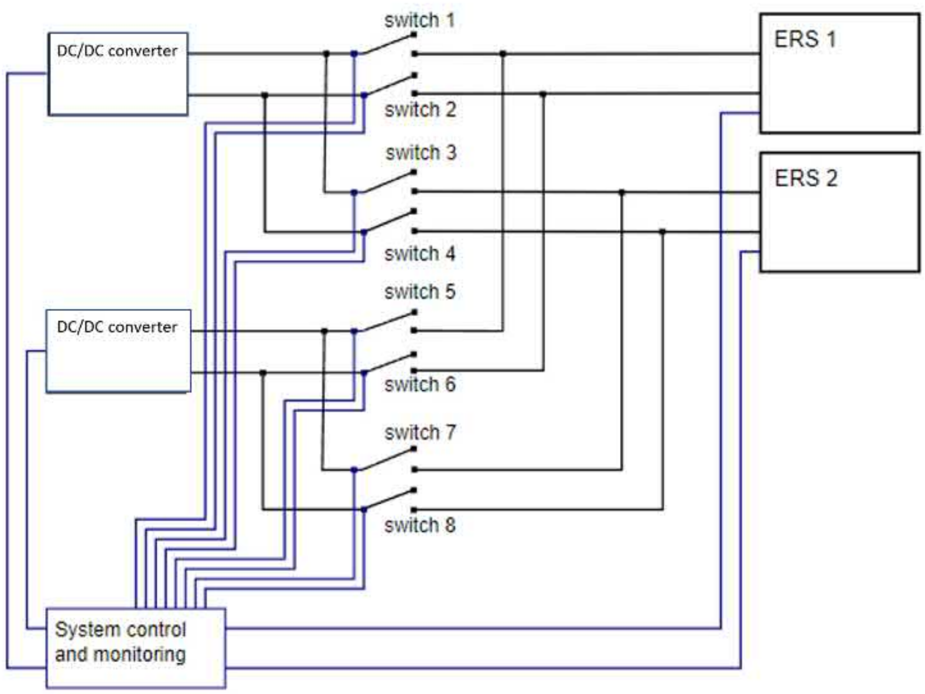


Figure 36: *Modular switch matrix model circuit*

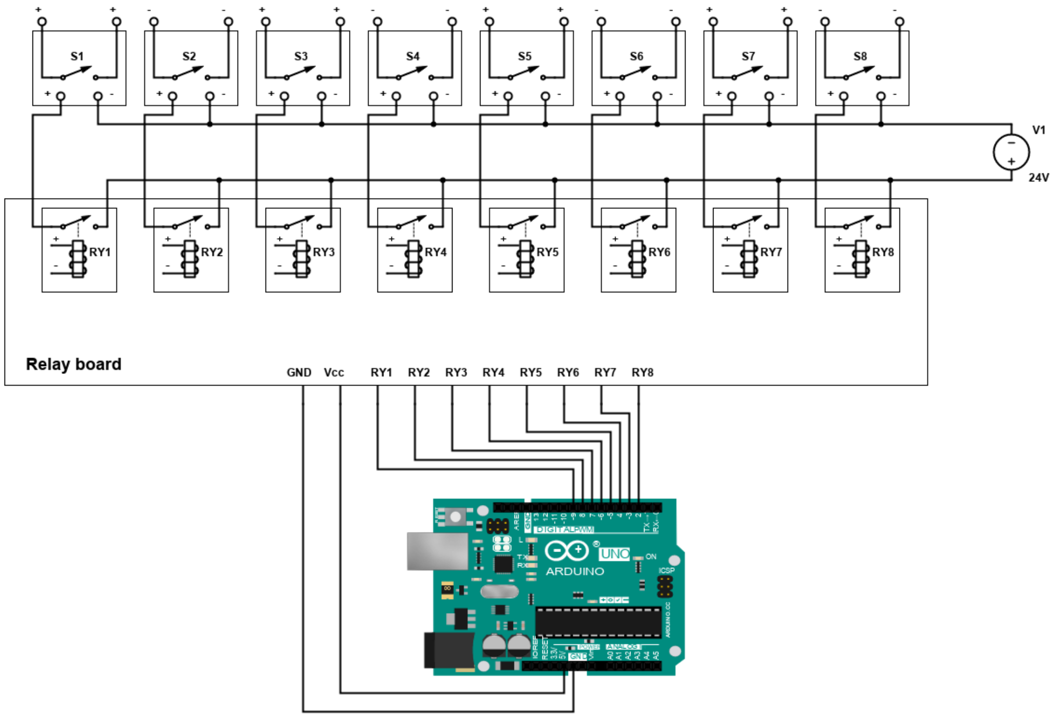


Figure 37: *Contactor control circuit*

4.1 Modular switch matrix model

The proposed modular switching charger is built on a small scale of two DC-DC converters and two charging positions each connected to an ERS tracks, Figure 36. The system control and monitoring should use standard CAN bus protocol to communicate with the charging spots when there is a truck that needs charging and with the DC-DC converters to control current output. The control unit also controls the switches when a converter is to be connected or disconnected to a charging position. It also monitors the current on both the DC-DC side and the charging position side of the switch and makes sure the DC-DC converter is off when switching occurs. Thus, the switching is done when the current is zero or very low such that there is no power flowing through the switch. This prevents electric arcs and allows the system to be built with less costly switches which would otherwise be needed to handle switching with high current flowing through it without damaging the system. However, for the prototype in this thesis the current from the converters is controlled via human input on the interface of the converter while the contactors are controlled via a micro-controller, in this case an Arduino Uno, Figure 37.

In the contactor control circuit, Figure 37, the contactors (S1-S8 in the figure) work as a powered switch, closing when 24V is applied to them. The Ardunio Uno however, can only provide an output voltage of 5V, thus a relay board module is connected between the Arduino and contactors to act as a switch for the 24V circuit. Each relay (RY1-RY8 in the figure) on the board is paired with a contactor for control and each pair is in parallel with each other in the 24V circuit. In the figure the pairs are S1-RY1, S2-RY2,..., S8-RY8. When RY1 gets a signal from the micro-controller its switch closes which closes the 24V circuit such that S1 receives 24V. This in turn closes the contactor which allows DC-DC converter 1's positive output to be connected to the ERS tracks positive input. The converter which needs both its positive output and negative output to be connected to the ERS tracks positive and negative input relies on two contactors to be switched at the same time. Therefore, the relay switches are programmed to work in pairs, RY1-RY2 to close S1-S2, RY3-RY4 to close S3-S4 and so forth. The code for the program can be seen in appendix B.

The DC-DC converters that are used in the build are 25kW converters, Figure 38, and the contactors used are the earlier mentioned ALEV 200A. The connected contactors are S1-S8 in Figure 39. The two ERS tracks are simulated by using two 9kW heating elements each with a resistance of 58Ω, Figure 40. Using current control on the converter the power output to the heating elements is determined by the equation:

$$P = R \cdot I^2 \tag{18}$$

The maximum current a heating element can receive is thus about 12,5A. To test with higher current more heaters can be connected in parallel, increasing the maximum power to 18kW, 27kW etc.

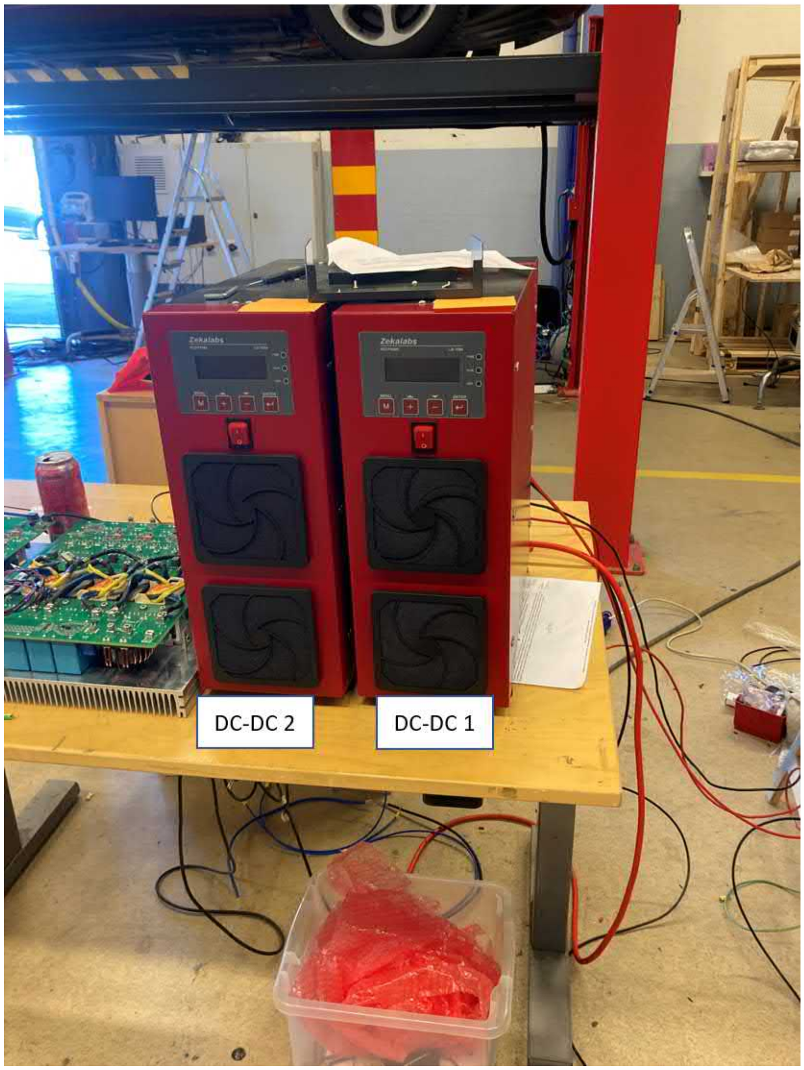


Figure 38: *DC-DC converters in the prototype*

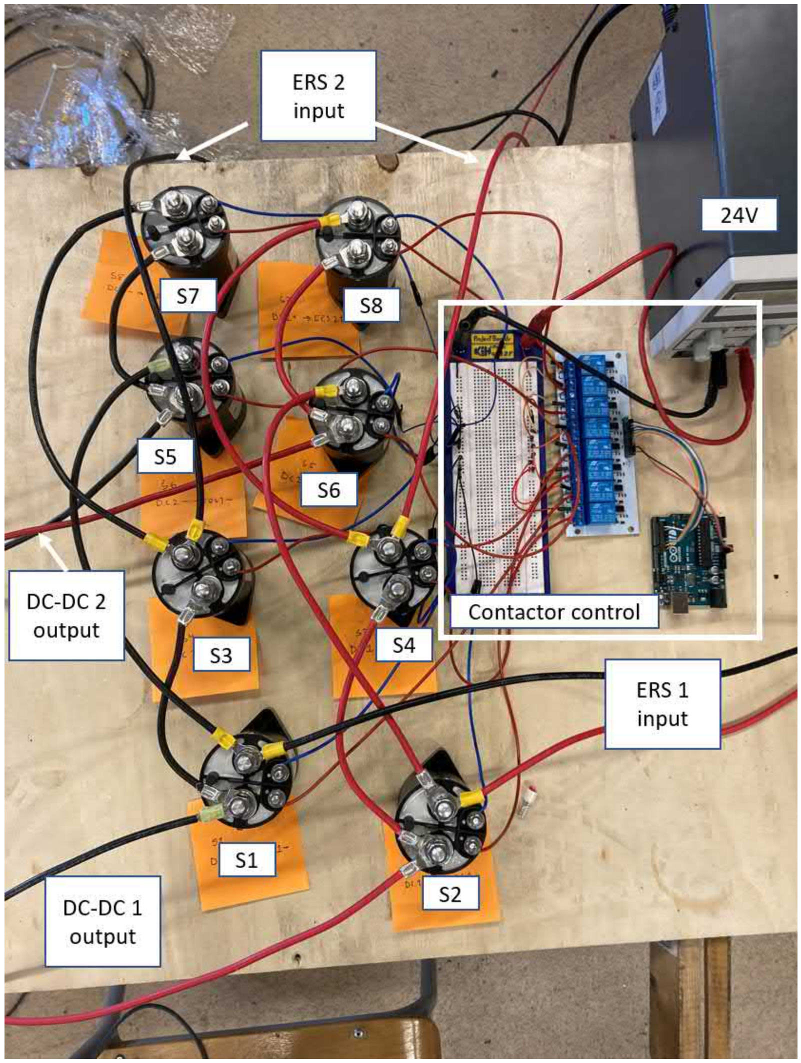


Figure 39: *The switch matrix together with the contactor control system*

Figure 40: *The heating elements used to simulate ERS rails*

4.2 Operating the prototype model

The following sequence was used to test the prototype:

1. Turn on Arduino and power the relay board with 24V.
2. Turn on converters in Stop mode (converter is on but not outputting), set current to 0A.
3. Close S1, S2, S7 and S8 with the Arduino script (Appendix B) such that each converter is connected to one heating element.
4. Set converter to Running mode (now outputting), increase current to 10A which sets the power to 5,8kW (eq 21).
5. Run for a while and feel that the elements get hot.
6. Decrease current to 0A on both converters.

7. Open S7, S8 and close S5, S6 with the Arduino script (Appendix B) such that both converters now is connected to one heating element.

8. Increase current to 5A on both converters which keeps the connected element at 5,8kW.

9. Run for a while to see that one element is still warm while the other cools down.

10. Repeat from 6 except with S3, S4, S7 and S8 closed and S1, S2, S5 and S6 open such that the converters now power the other heating element.

11. To turn off the system. Set currents to 0A, put converters in Stop mode and then turn off. Open all switches, disconnect 24V source and turn off the Arduino.

4.3 Prototype results

The following figures in this sections shows the results of the prototype when operating according to the list in the previous section. The pictures of the heating elements are taken with an infrared camera to shows which element is turned on. Figure 41 follows point 1 and 2 from the list of operation. In picture A it is visible that the converters are outputting 0A and with no relays turned on (picture B) no contactor is closed. Thus, the elements are not turned on and has a low temperature seen in picture C.

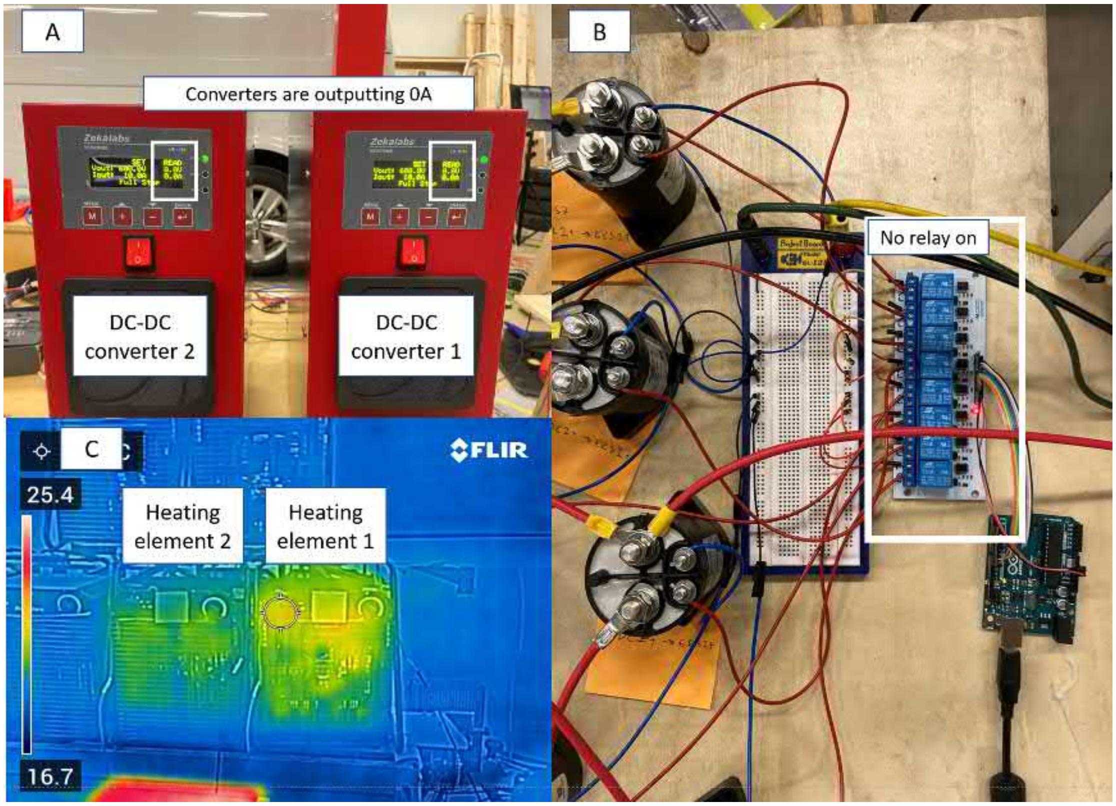


Figure 41: *Pictures showing the prototype operating from point 1 and 2 from the operating list*

Figure 42 follows point 3-5 from the list of operation. Picture A shows that contactor S1,S2, S7 and S8 which connects DC-DC converter 1 with heating element 1 and DC-DC converter 2 with heating element 2. Picture B shows that both converters are outputting 10A each which powers the heating elements which can be seen in picture C.

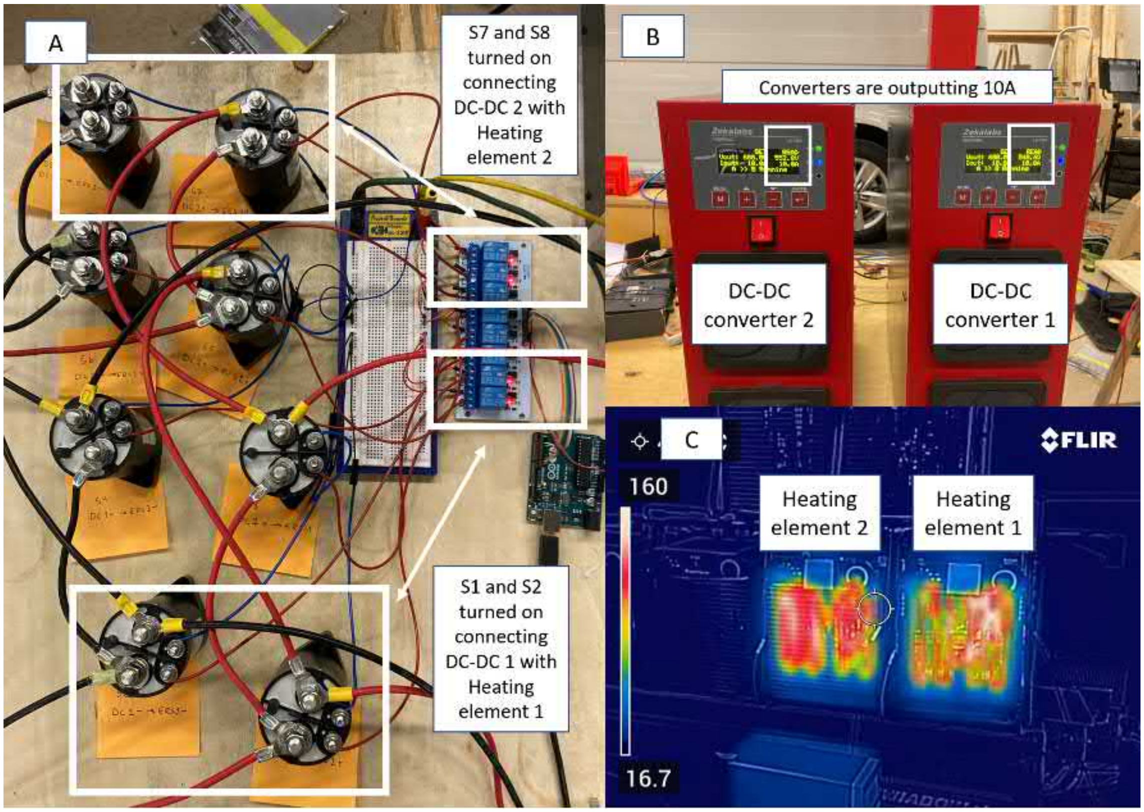


Figure 42: *Pictures showing the prototype operating from point 3-5 from the operating list*

Figure 43 follows point 6-9 from the list of operation. Picture A shows that the current of both converters is decreased to 0A. In picture B the relays switch such that contactor S1, S2, S5 and S6 is closed which connects both converters to heating element 1. In picture C the current is increased to 5A on both the converters such that only heating element 1 is powered, seen in picture D.

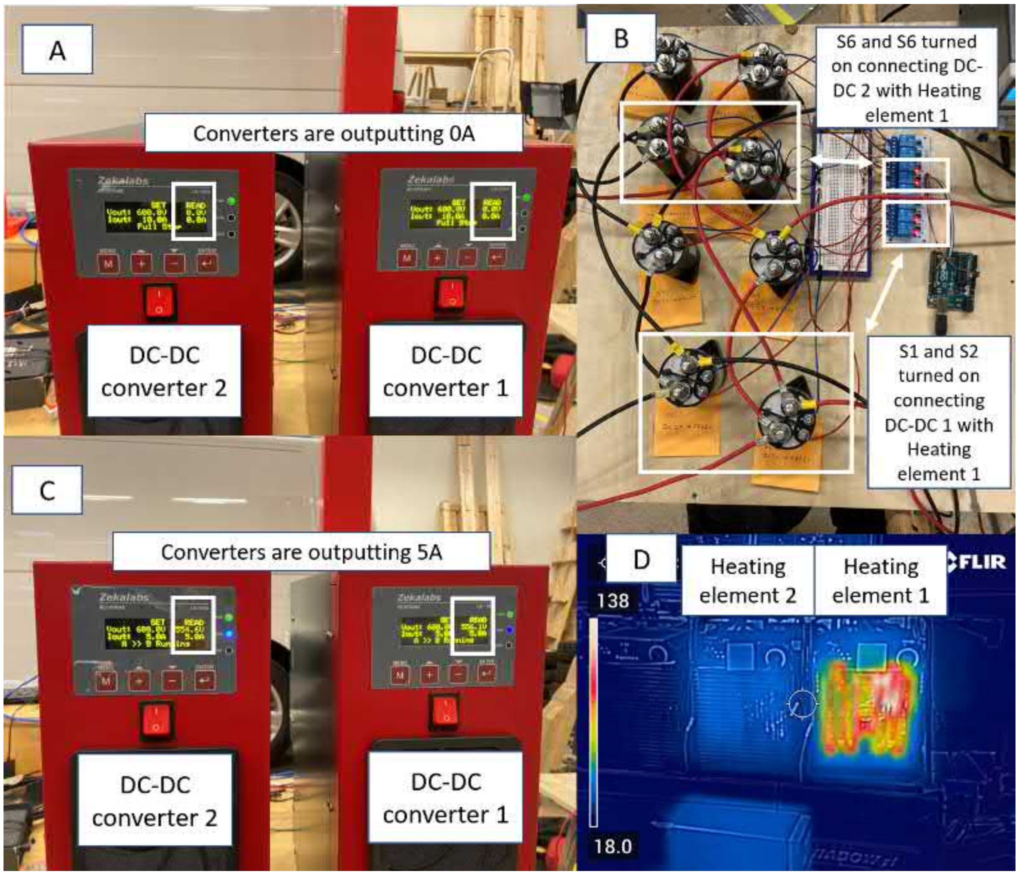


Figure 43: *Pictures showing the prototype operating from point 6-9 from the operating list*

Figure 44 follows point 10 from the list of operation. Picture A shows that the current of both converters is decreased to 0A. In picture B the relays switch such that contactor S3, S4, S7 and S8 is closed which connects both converters to heating element 2. In picture C the current is increased to 5A on both the converters such that only heating element 2 is powered, seen in picture D.

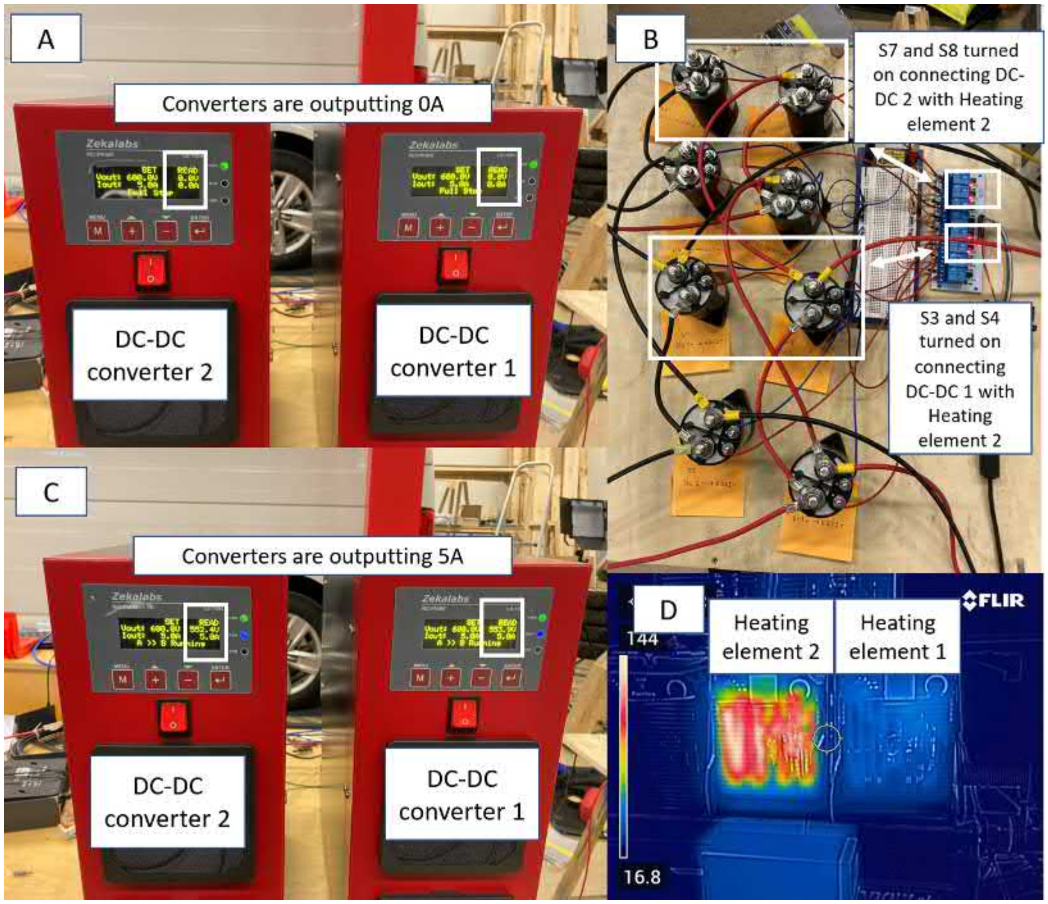


Figure 44: *Pictures showing the prototype operating from point 10 from the operating list*

5 Discussion

Logistics companies are highly dependent on time spent delivering goods versus time spent charging, wanting a quick and efficient system that can fast charge the trucks during the day but also a system that is able to provide slower charging during the night. Having several independent fast chargers is not only more expensive due to the large number of DC-DC converters but the robustness of the system is compromised. Having a switch matrix, which can reroute converters as needed to different charging spots, grants the charger the ability to cover for potential failures which increases the up-time for the charger and thus availability. This is a potential upside for the switch matrix charger as it is beneficial for the terminal and customers who use the charger if the up-time is increased due to less waiting, which in a logistics company costs money. A charger built with fewer converters, as mentioned, is also beneficial. Not only for the reduced cost of purchasing a lower number of converters but also due to the ongoing silicon and semi-conductor shortage, which ramps up the price of those.

5.1 Charge time and optimal size of the converter

Having a short daytime charge time is important for a logistics company, as when the trucks stand still they cost money. The reason lunch was chosen for daytime is that a lunch break usually is around 30 min and that would be a good time to charge since the driver is on break and the truck will stand still anyway. However, since the trucks in reality will be out on their routes there might not be a possibility to return to the terminal to charge [34], thus any 30 min during the day works just as well for the calculations done in this thesis. Looking at Table 11 and comparing Table a) to b), Longest charge time first versus Shortest charge time first, it becomes quite clear that the fastest alternative to charge a whole fleet, first truck to the last truck, would be to allow the trucks with the longest charge time to go first. The total time is lower in every case as seen in the table. However, if the goal is to charge as many trucks as possible in a short time it is more beneficial to have the trucks with the shortest time go first. In every case the majority of trucks are charged in the first 30 min window. Interesting side note is that in Table B for the 3MW system for converter sizes 25kW and 50kW the three trucks that do not manage in 30 min is the three trucks from Table 9 that always, no matter the configuration, needs a charge time longer than half an hour due to their energy consumption during the day. Actually, they show up in every case in both Table a) and b), especially in b) there they always are the last ones to be done.

As for the size of the DC-DC converters installed, 50kW or 100kW gives the best charge times in most of the cases. Comparing the converters power resolution from appendix A it is somewhat apparent from just viewing the graphs that smaller converters give better resolution than larger.

The first reason is purely a division problem from the numbers that have been chosen for both the converters and installed power. 25kW, 50kW and 100kW is all evenly divisible with 1MW, 1,5MW, 2MW and 3MW while 150kW is only evenly dividable with 1,5MW and 3MW, and 200kW is only evenly divisible with 1MW, 2MW and 3MW. Thus, in the cases where the converters do not divide evenly there will automatically be converters that only outputs some of its intended power. Second reason is that not all trucks need the full amount of power a converter can provide. If a truck only needs 25kW charge but a 200kW converters is installed, the full converter will be dedicated to that truck but 175kW of the power would not be in use. It becomes very apparent in all graphs for the 200kW converter, appendix A5, that even though all the installed converters in the charger are in use the power output never reaches its maximum installed power. Smaller converters are also easier to divide among the trucks. Comparing 50kW and 100kW converters, the graphs in appendix A2 and A3, the 50kW does use the installed converters a bit better but the difference is not that big. Choosing between them comes down to costs and availability on the market. Using smaller converters has the drawback of requiring a higher number of switches (depending on the installed power of the charger) which is a large portion of the total cost of the charger as seen in subsection 3.4.5 (Figure20 to Figure 27). Comparing 50kW and 100kW in both models, model version 1 Figure 21 and model version 2 Figure 25, the 50kW is about 1/3 more costly than 100kW converters in every case. The main reason being the number of required contactors.

5.2 Full scale model and implementation at terminal

The resulting difference between having the ERS input busbars going horizontally (model version 1) versus going vertically (model version 2) is only the size of the structure, and hence the number of busbars required. Comparing the cost of both models, model version 1 with Cu busbars (Figure 20) and Al busbars (Figure 21) with model version 2 with Cu busbars (Figure 24) and Al busbars (Figure 25), model 2 is slightly more expensive than model 1 only due to the busbars. However, the difference is only about thousands of euros if aluminium busbars are chosen compared to in the tens of thousands euros if copper busbars are chosen. It becomes quite evident why Al busbars are the better alternative in either model at $\frac{1}{10}$th the cost of Cu busbars. Aluminium is also less prone to robbery if implemented. Model 2s size and thus cost is highly dependent on both the number of vertical busbars (the number of charging spots) and horizontal busbars (number of DC-DC converter), while model 1 size and cost is almost only dependent on its vertical busbars (number of DC-DC converters). Therefore model 2 will see a larger change in the cost than model 1 if the number of charging spots is changed. In the calculations the number of charging spots were constant at 55 spots whereas the number of converters and installed power of the charger varied. Furthermore, when connecting the charger structure to the ERS rails it might be from an aesthetic point of view preferable with model 2 where the vertical ERS input busbars can connect to cables which run straight down in the ground to be concealed and later drawn to their dedicated ERS rail. While in model 1 the horizontal ERS input busbar would result in a "waterfall" of cables out one wall.

The conventional charger model, compared to the two switch matrix models, requires a far larger number of DC-DC converters to cover all charging spots with fast chargers but the number of contactors and busbars are significantly reduced due to no switch matrix structure. Due to the large number of converters needed in the conventional charger the cost is more than doubled when compared to the switch matrix models. See the comparison in Table 33. The cost of having fast chargers at every charging spot is taken from Figure 31 and is compared to a 3MW switch matrix charger (which is able to charge the whole fleet in 30min) from Figure 21 and Figure 25.

Converter size	Conventional	Model version 1	Model version 2
25kW	€1944·10^3	€808·10^3	€818·10^3
50kW	€1315·10^3	€456·10^3	€461·10^3
100kW	€928·10^3	€268·10^3	€272·10^3
150kW	€749·10^3	€339·10^3	€342·10^3

Table 33: *Cost of a conventional fast charger system with fast chargers at every charging spot compared with the cost of the switch matrix charger system version 1 and 2 with a total installed power of 3MW*

However, from the earlier mentioned interview with Jonas Olsson at Bring the actual number of trucks that need fast charging during the day is at maximum 10 trucks since most trucks would charge elsewhere while out on their routes, and all 10 will not come in and charge at the same time [34]. For the switch matrix charger a charger structure with a total installed 1MW would be able to cover for 10 trucks that need fast charging (Table 11) and be able to cover for all trucks when night charging (calculated in the previous project to be <500kW) (Table 1). Comparing the 1MW charger structure from Figure 21 and Figure 25 with the conventional charger model with only a few fast chargers and the rest night chargers, from Figure 33 and Figure 35, the cost is still higher for the conventional charger due to the increased number of converters needed as can be seen in Table 34.

Converter size	Conventional (25kW night chargers)	Conventional (50kW night chargers)	Model version 1	Model version 2
25kW	€475·10^3	€514·10^3	€270·10^3	€273·10^3
50kW	€361·10^3	€400·10^3	€152·10^3	€154·10^3
100kW	€291·10^3	€330·10^3	€90·10^3	€91·10^3
150kW	€262·10^3	€301·10^3	€119·10^3	€119·10^3

Table 34: *Cost of conventional fast chargers with dedicated night charging spots of either 25kW or 50kW compared with the cost of the switch matrix charger system version 1 and 2 with a total installed power of 1MW*

Lastly, the models constructed in this thesis are more rough sketches. Future work would be to investigate how to properly build the models, in particular the connection of switches to the busbars. In the prototype a lot of cables were needed to connect the contactors to the converters and heating elements which for the full scale system might be undesirable due to the increased complexity. IGBTs on PCB boards might be a better solution to contactors as they are significantly smaller and cost around the same if smaller converters are used, see Figure 21 compared to Figure 23 and Figure 25 compared to Figure 27. More future work would also be to investigate the charger placement at the terminal. From the Bring interview, wanting to have the charger close to the existing transformer was desirable. However, depending on which size of charger is needed another place must be chosen and another transformer to be installed which adds construction and costs. Furthermore, the charger is not necessarily limited to be used at logistics terminals for trucks. Constructing the charger as a charging station at rest stops, along highways or as conventional gas stations allows for cars to use the charging as well as the trucks that do not charge at the terminal. At those places the charging structure will not necessarily be limited by space as at a terminal and 3MW chargers and even larger chargers is a possibility allowing 50+ vehicles to charge at the same time if necessary.

5.3 Comments on prototype

The initial plan was to also control the converters with a computer with CAN bus communication together with the contactor control. However, due to my own unfamiliarity with CAN and control of DC-DC converters that idea was scrapped and it was chosen that human control via the converter interface was good enough. The relay switches to activate the contactors were also unplanned but a necessary solution to be able to provide the contactors with 24V when they are to be switched. A similar solution is probably needed for a full scale charger where the same number of relays as switches would be needed. This will be an added cost which has not been included in this thesis. Worth to note is that the relays need to be able to handle 24V which does not call for the most expensive relays on the market. The one in the prototype was an 8x relay module and cost about 300kr.

5.4 Conclusion and final thoughts

My conclusion from this thesis is that the switch matrix charger is possible to build and is cheaper than implementing conventional chargers at the terminal, especially the smaller version where only a few trucks need fast charging at the terminal. The charger offers a robust and flexible system with fewer installed converters, beneficial in times of semi-conductor shortage. The prototype proves that the switch matrix i feasible even though more engineering work as to be done to fully automate it. The transition from conventional cars to EVs is well underway and will require new infrastructure projects to be able to facilitate enough charge to provide the EVs with the same or even longer driving range. I hope this thesis has opened up for more possible solutions mainly when it comes to electrifying the transport of goods sector but also questions of which way is best to go when it comes to charging for all types of EVs.

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Appendices

A Simulation results - Use of available power and utilization of DC-DC converters

Below is the graph result from the simulation done in section 3.2. The bars represent the power usage and maps to the left y-axis. The dotted line represents the number of DC-DC converters in use and maps to the right y-axis. If the bars are at the same level as the dotted line all of the power available from the converters in use are utilized. If the bars are lower than the dotted line means that some of the converters are not running at their potential maximum output.

A.1 25kW DC-DC converter

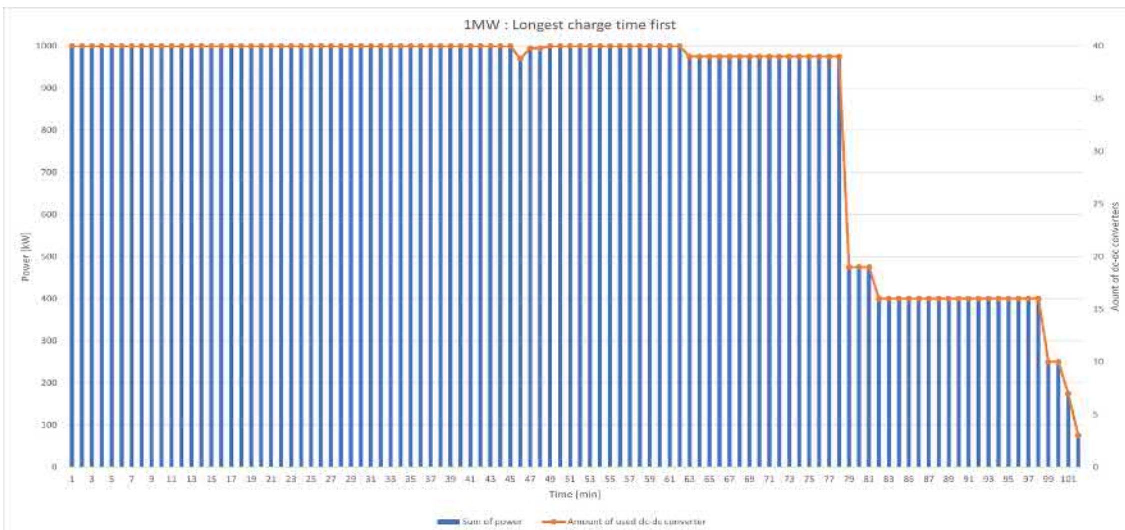

Figure 45: *Longest charge time first, 1MW charger with 25kW converters*

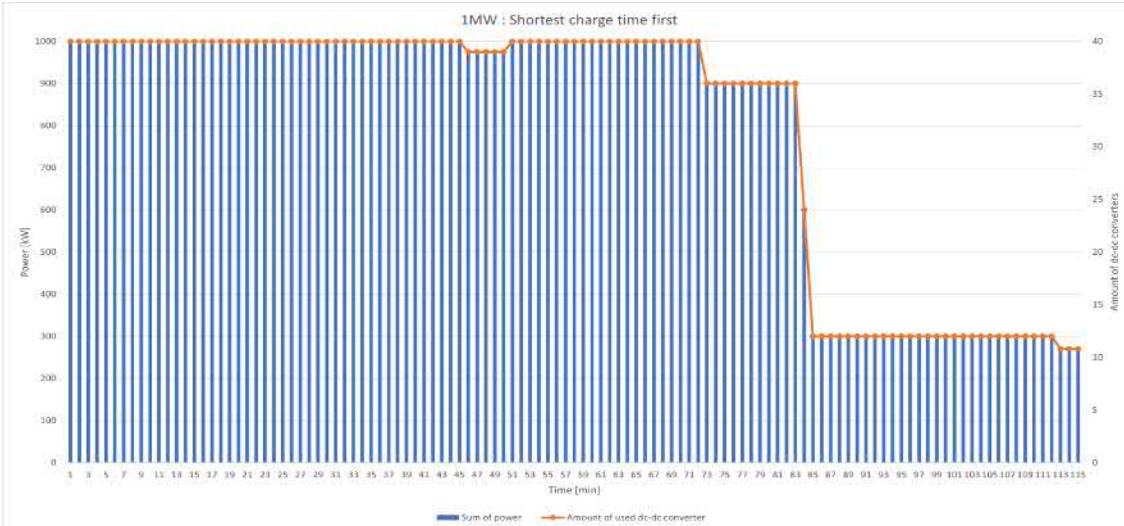

Figure 46: *Longest charge time first, 1.5MW charger with 25kW converters*

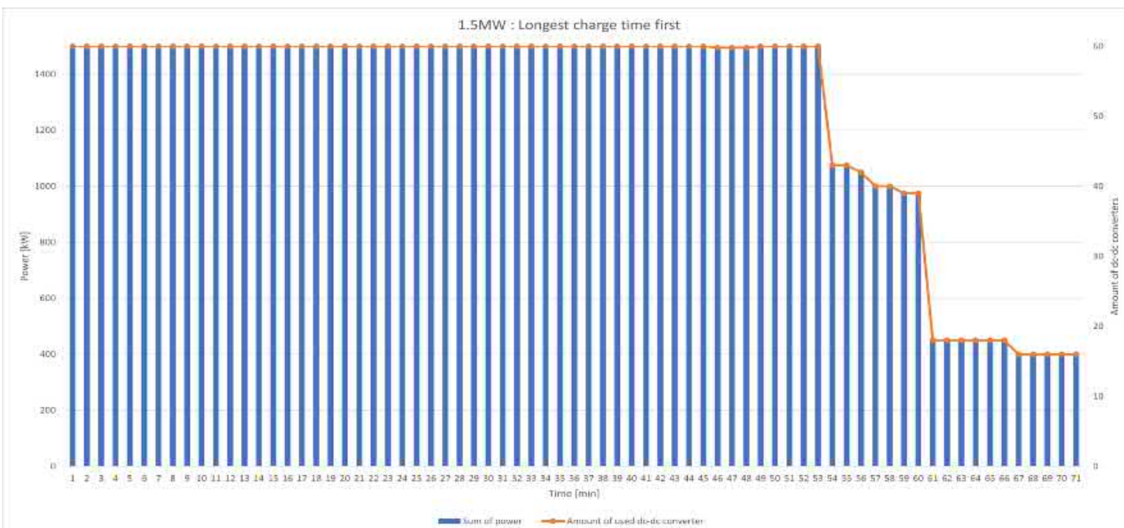

Figure 47: *Longest charge time first, 2MW charger with 25kW converters*

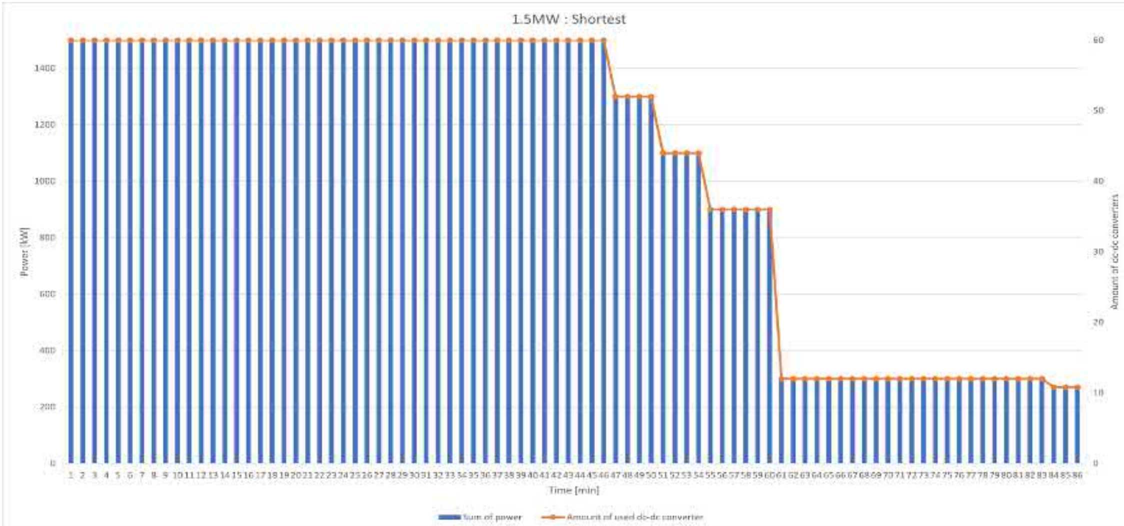

Figure 48: *Longest charge time first, 3MW charger with 25kW converters*

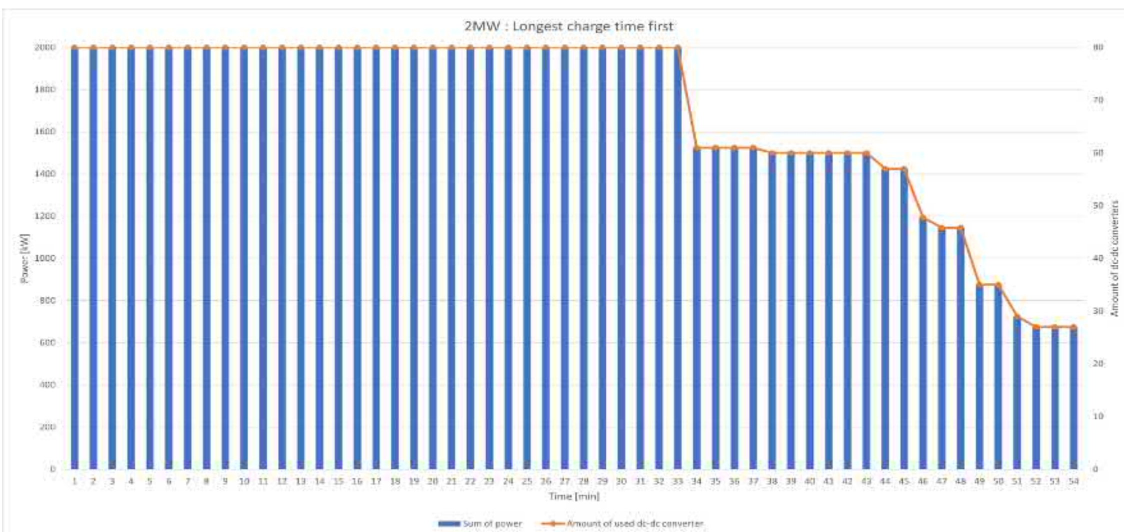

Figure 49: *Shortest charge time first, 1MW charger with 25kW converters*

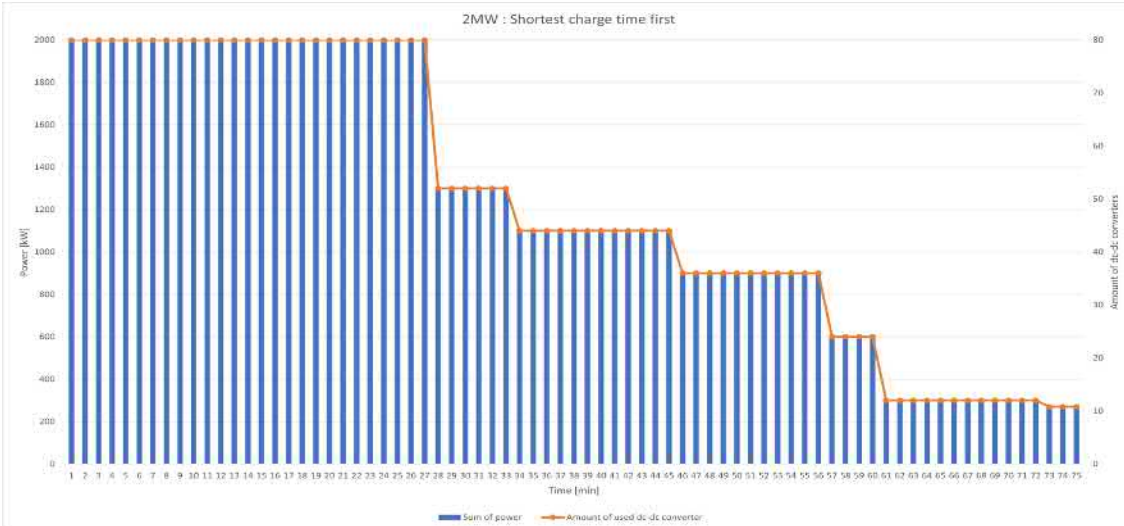

Figure 50: *Shortest charge time first, 1.5MW charger with 25kW converters*

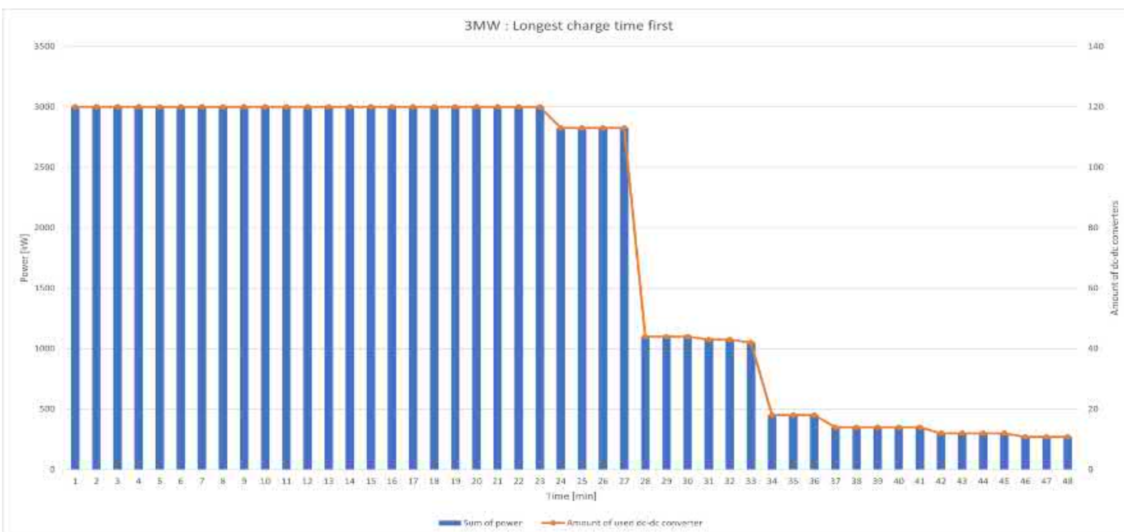

Figure 51: *Shortest charge time first, 2MW charger with 25kW converters*

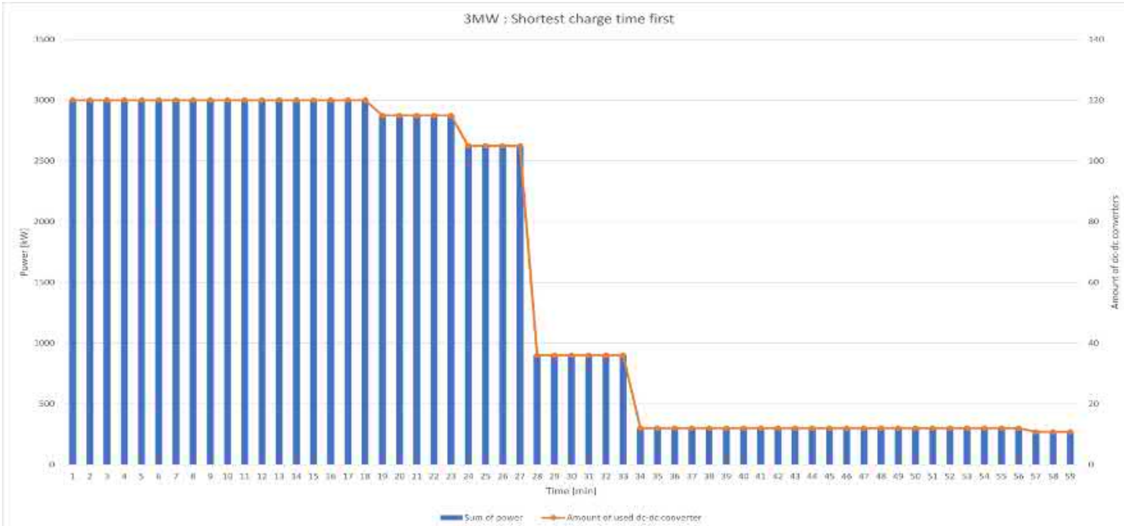

Figure 52: *Shortest charge time first, 3MW charger with 25kW converters*

A.2 50kW DC-DC converter

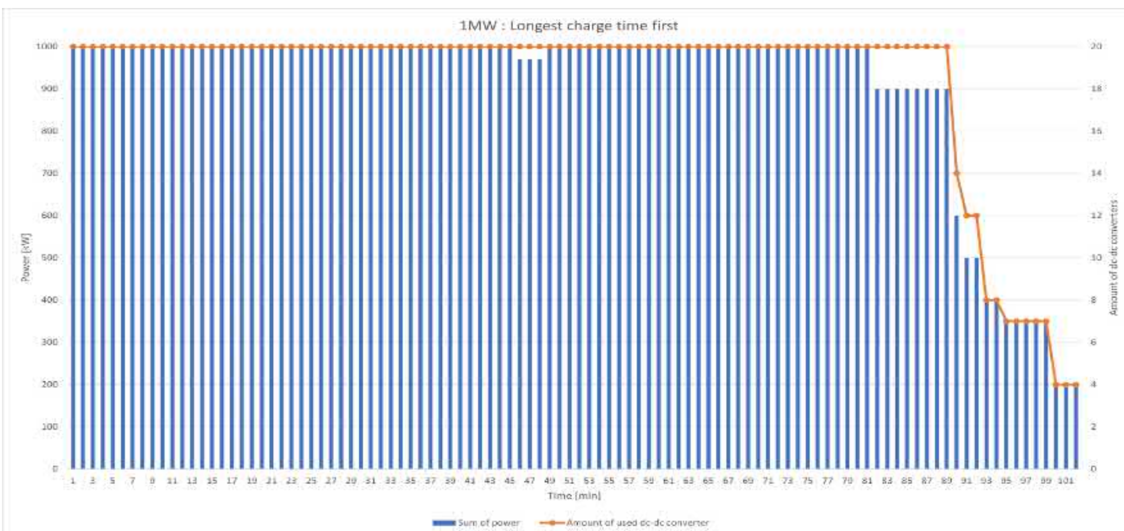

Figure 53: *Longest charge time first, 1MW charger with 50kW converters*

Figure 54: *Longest charge time first, 1.5MW charger with 50kW converters*

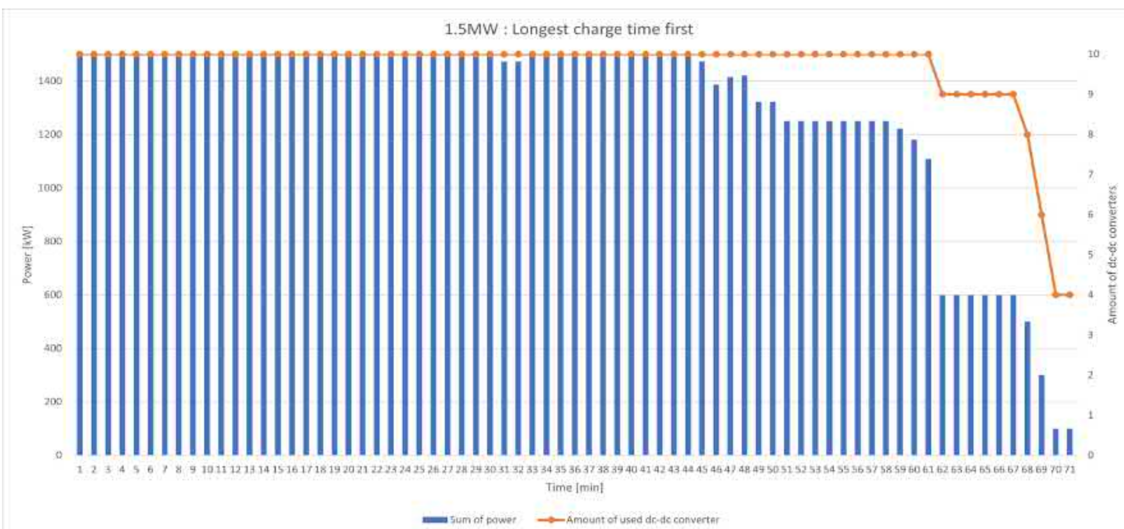

Figure 55: *Longest charge time first, 2MW charger with 50kW converters*

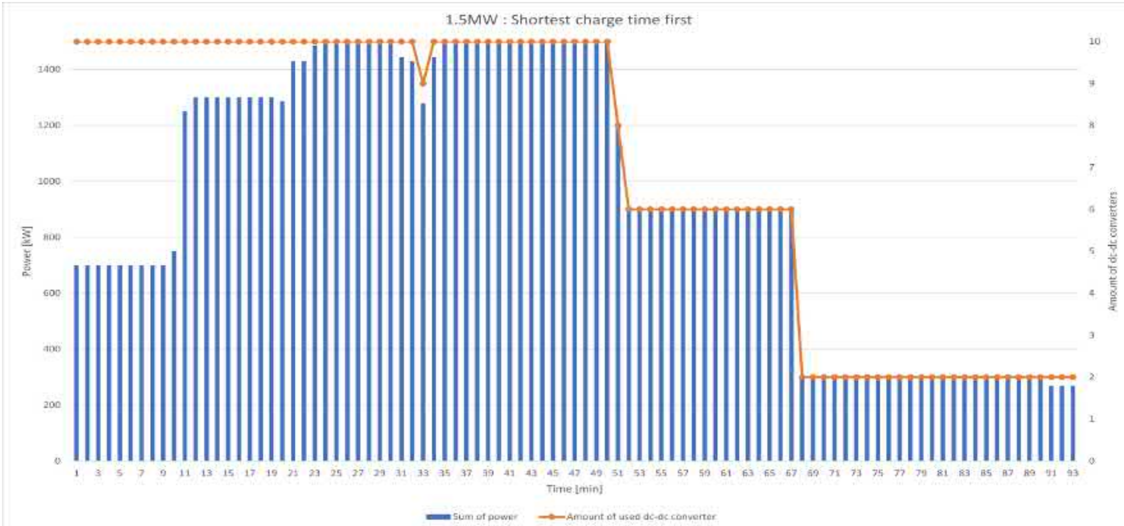

Figure 56: *Longest charge time first, 3MW charger with 50kW converters*

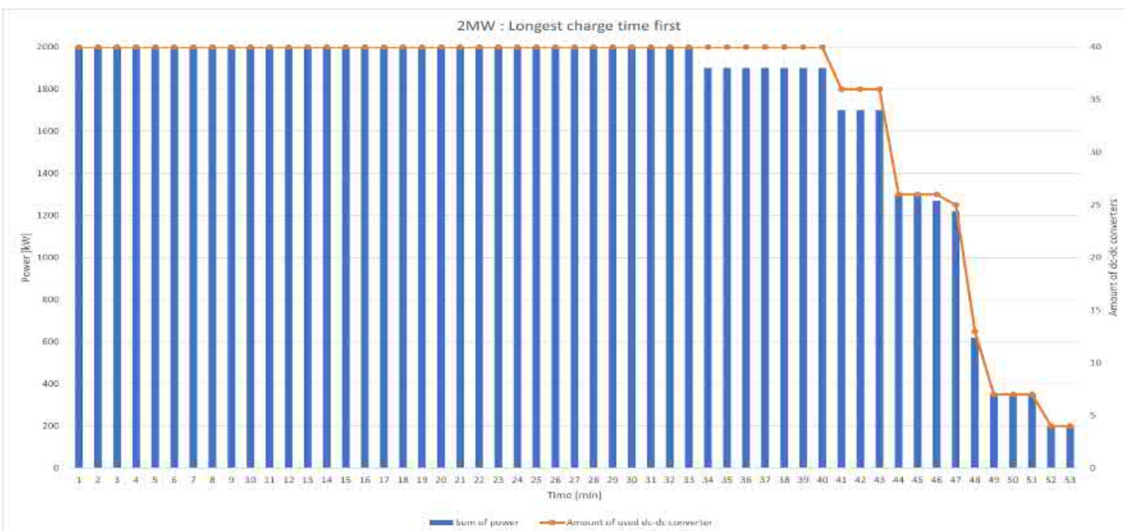

Figure 57: *Shortest charge time first, 1MW charger with 50kW converters*

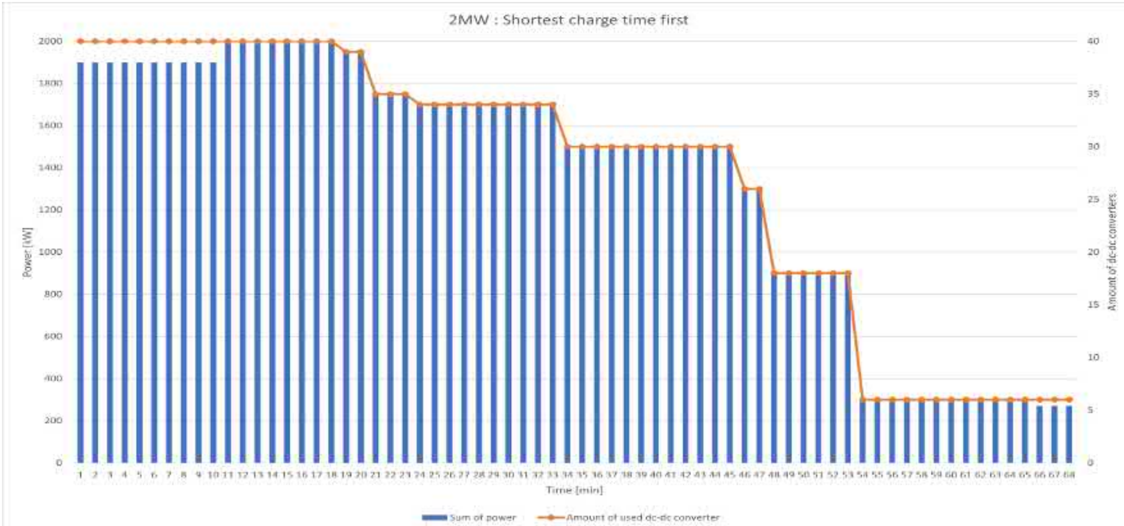

Figure 58: *Shortest charge time first, 1.5MW charger with 50kW converters*

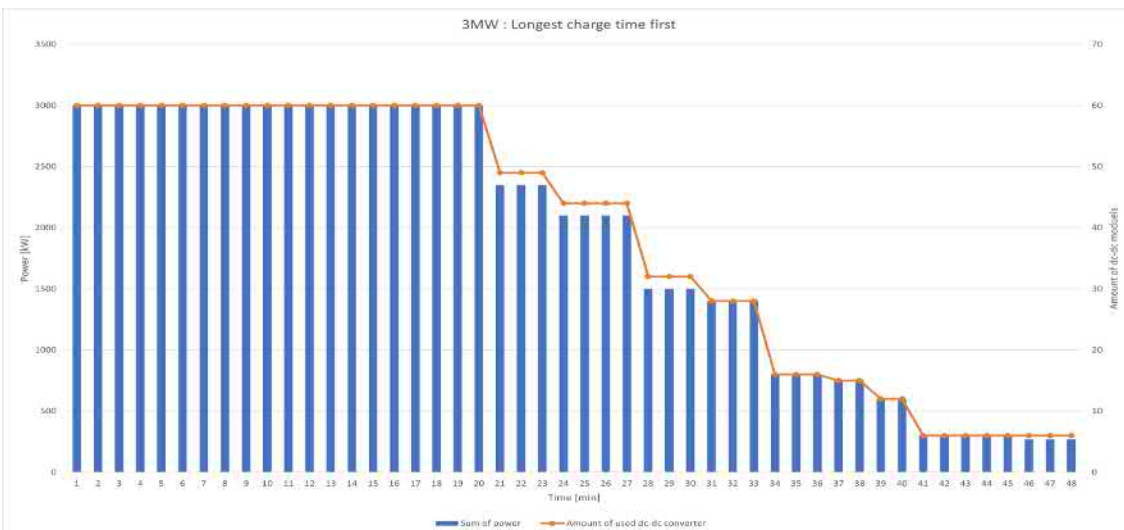

Figure 59: *Shortest charge time first, 2MW charger with 50kW converters*

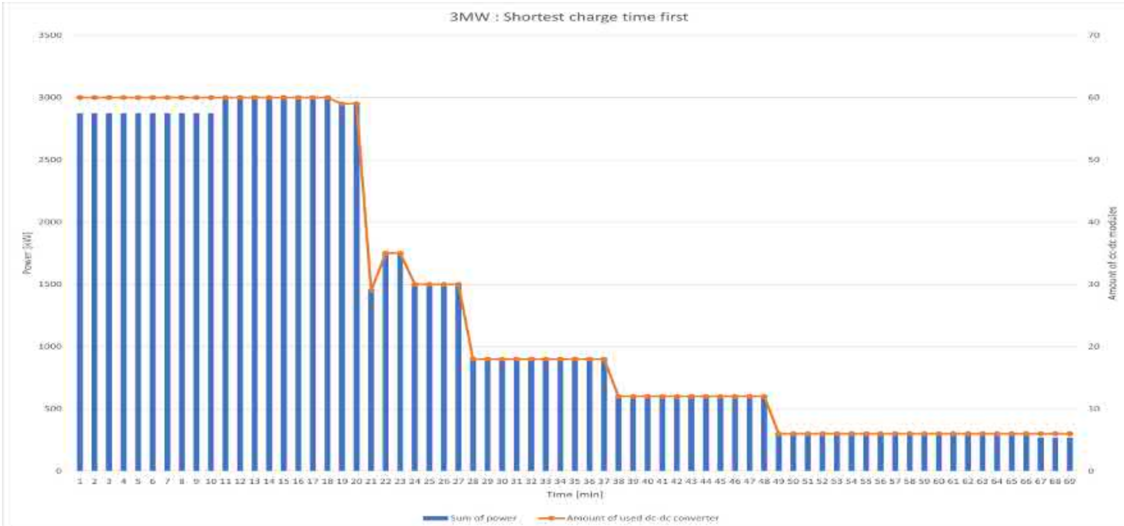

Figure 60: *Shortest charge time first, 3MW charger with 50kW converters*

A.3 100kW DC-DC converter

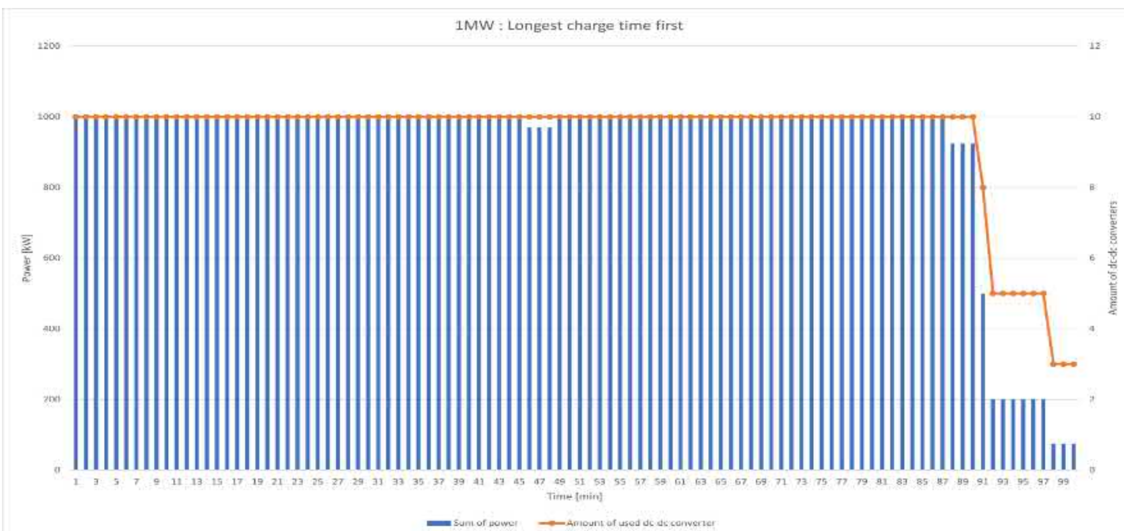

Figure 61: *Longest charge time first, 1MW charger with 100kW converters*

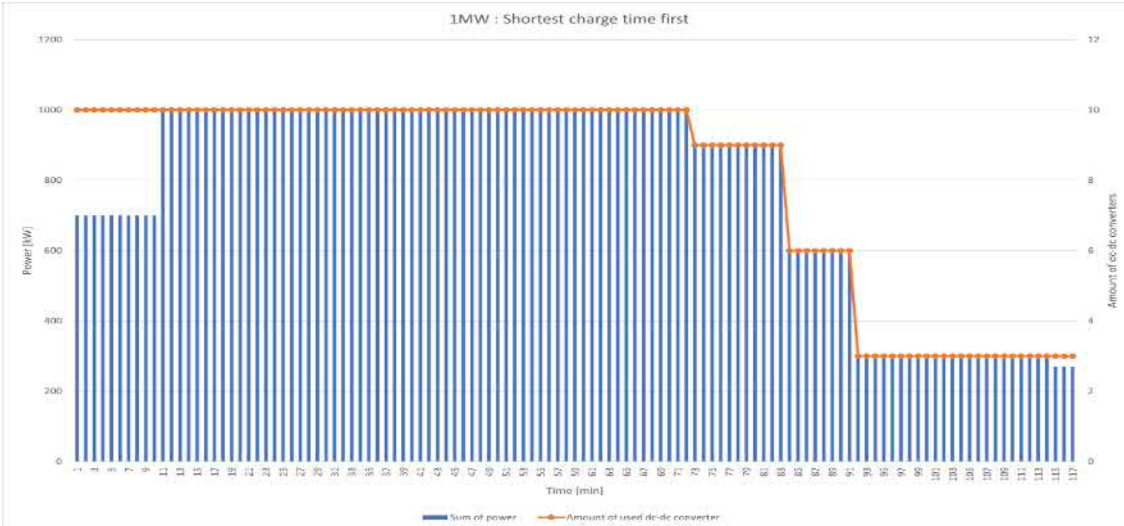

Figure 62: *Longest charge time first, 1.5MW charger with 100kW converters*

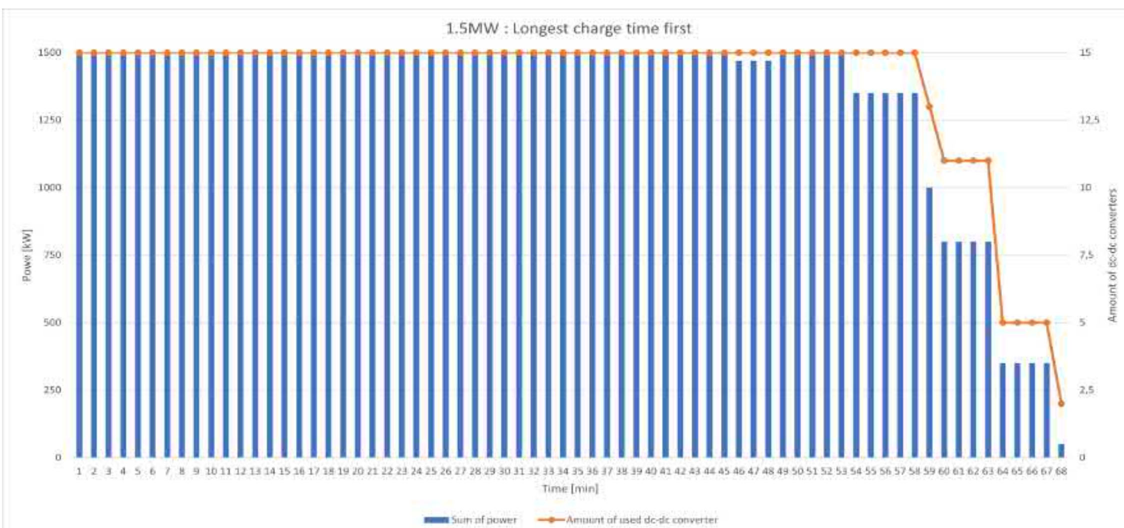

Figure 63: *Longest charge time first, 2MW charger with 100kW converters*

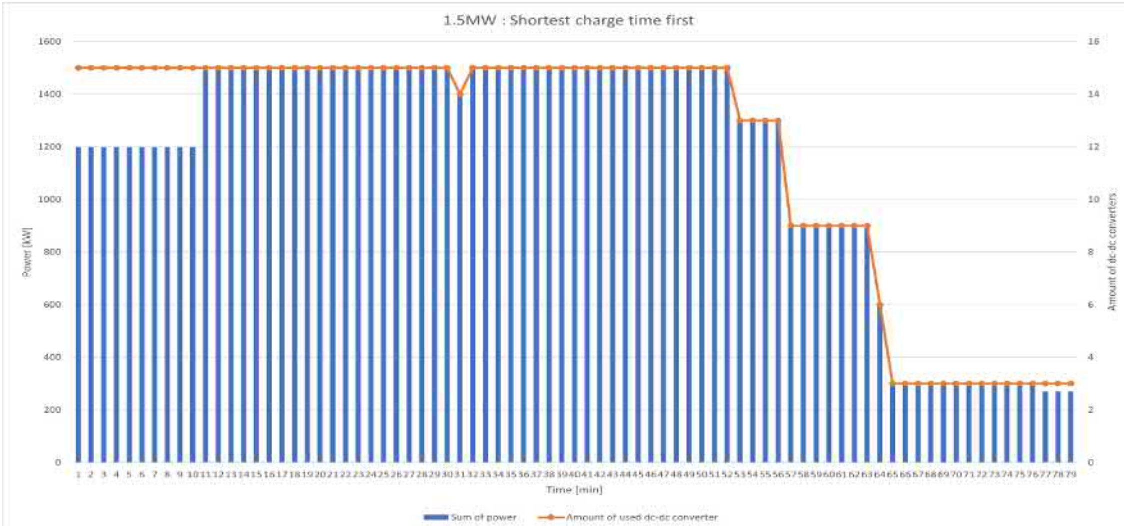

Figure 64: *Longest charge time first, 3MW charger with 100kW converters*

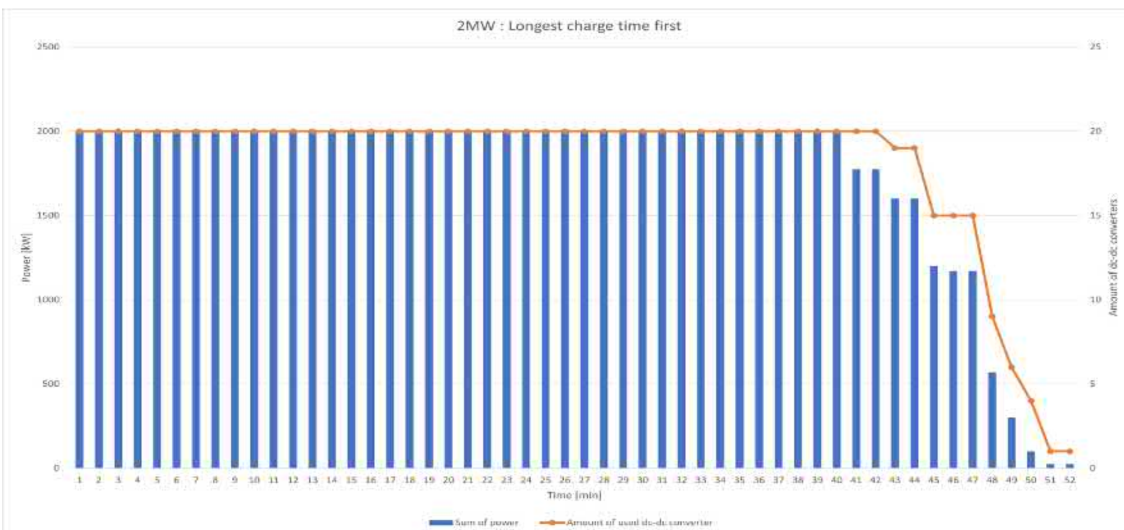

Figure 65: *Shortest charge time first, 1MW charger with 100kW converters*

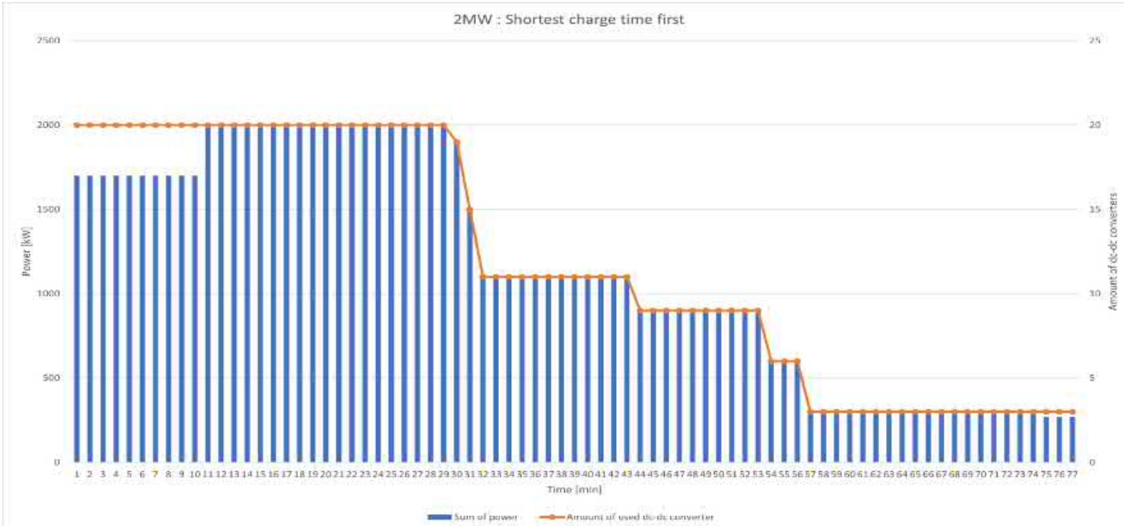

Figure 66: *Shortest charge time first, 1.5MW charger with 100kW converters*

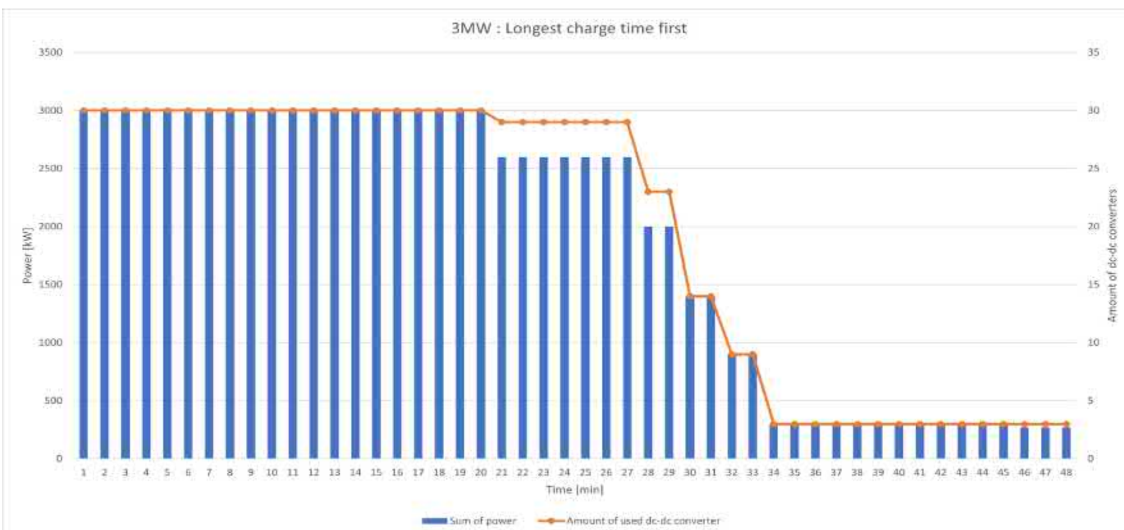

Figure 67: *Shortest charge time first, 2MW charger with 100kW converters*

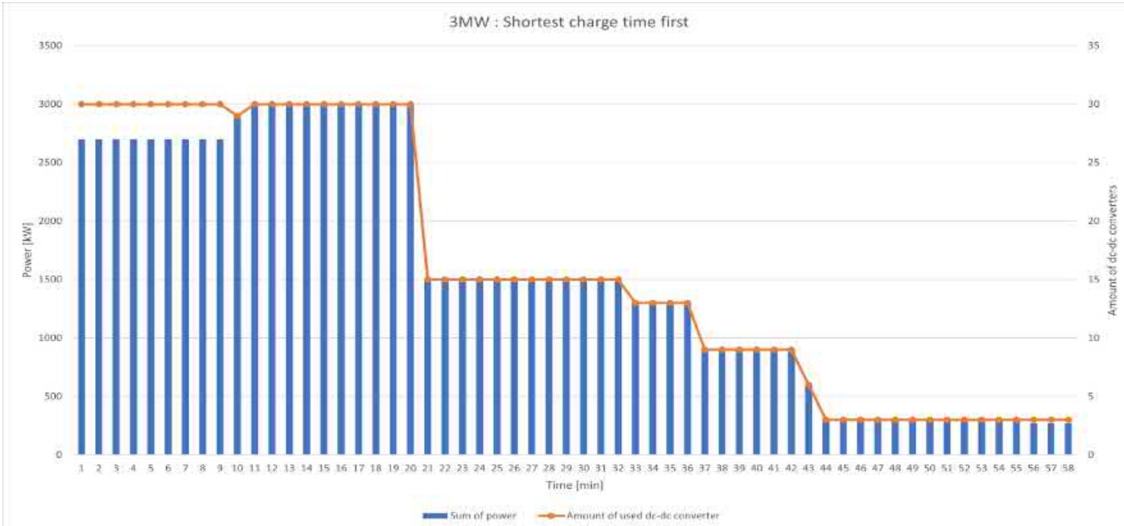

Figure 68: *Shortest charge time first, 3MW charger with 100kW converters*

A.4 150kW DC-DC converter

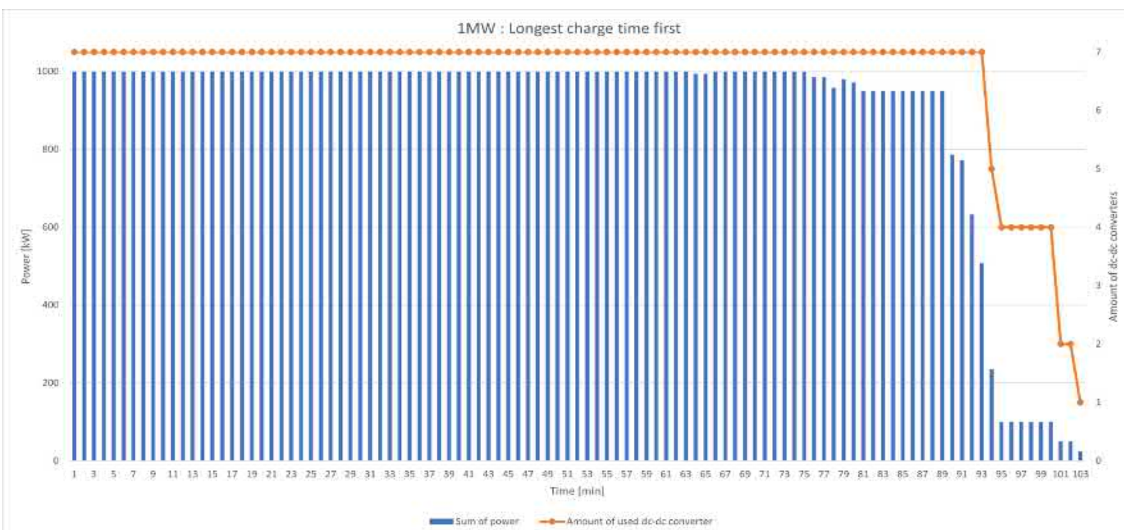

Figure 69: *Longest charge time first, 1MW charger with 150kW converters*

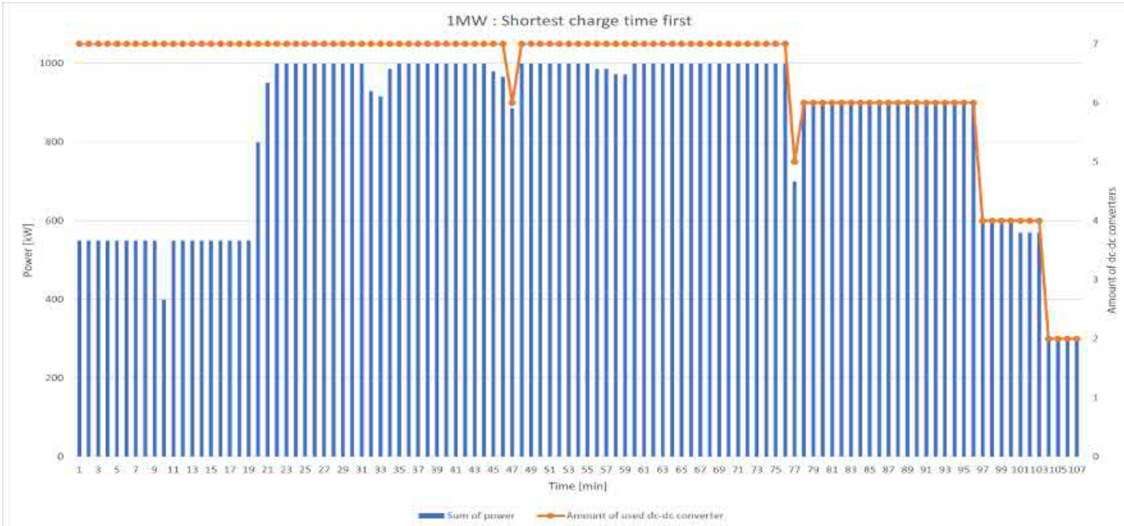

Figure 70: *Longest charge time first, 1,5MW charger with 150kW converters*

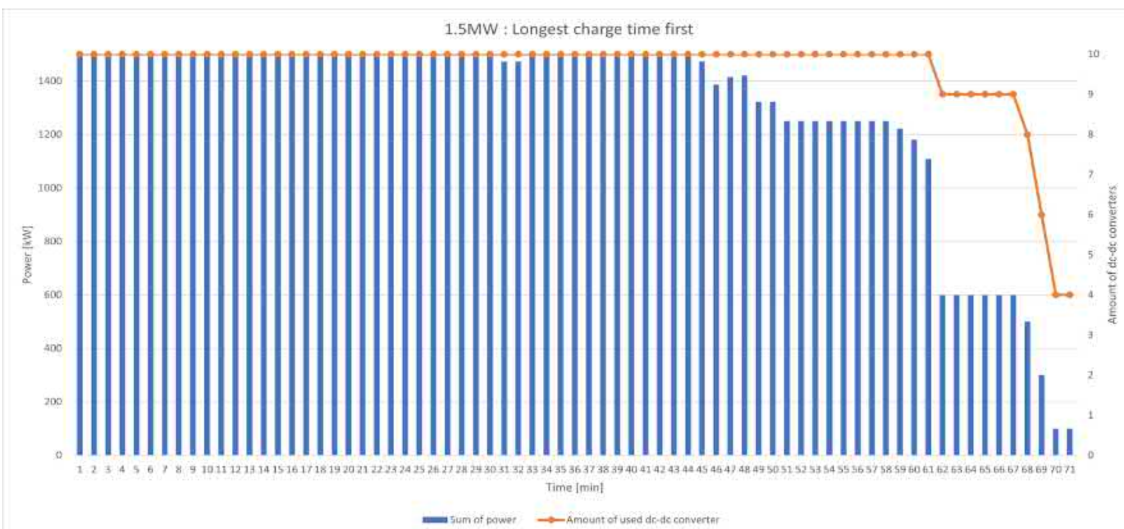

Figure 71: *Longest charge time first, 2MW charger with 150kW converters*

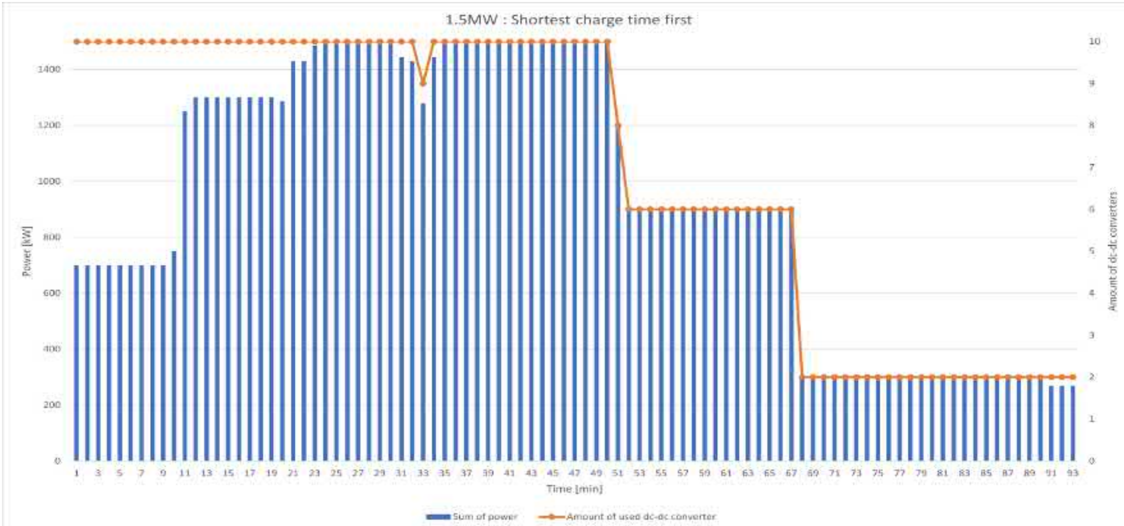

Figure 72: *Longest charge time first, 3MW charger with 150kW converters*

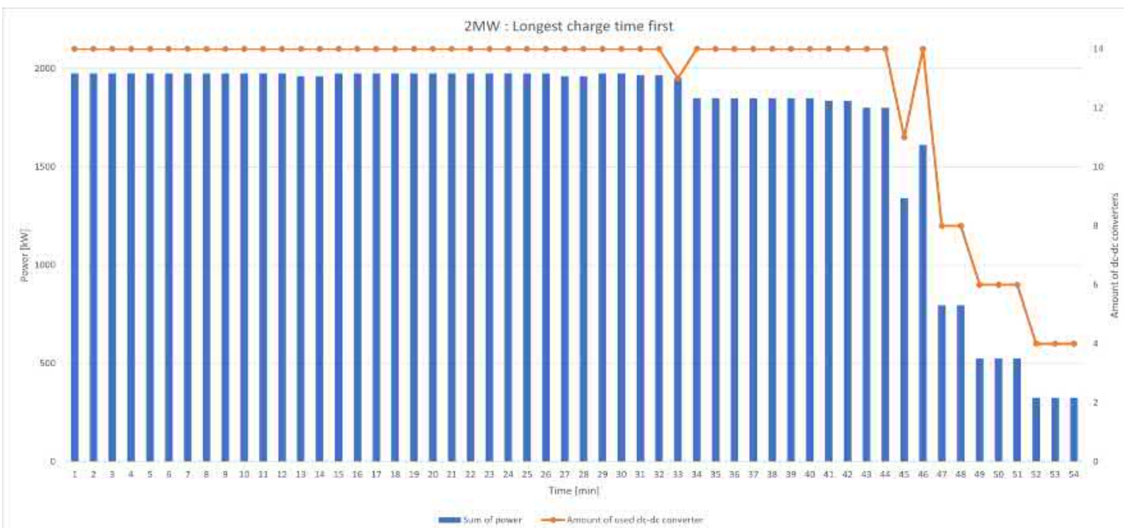

Figure 73: *Shortest charge time first, 1MW charger with 150kW converters*

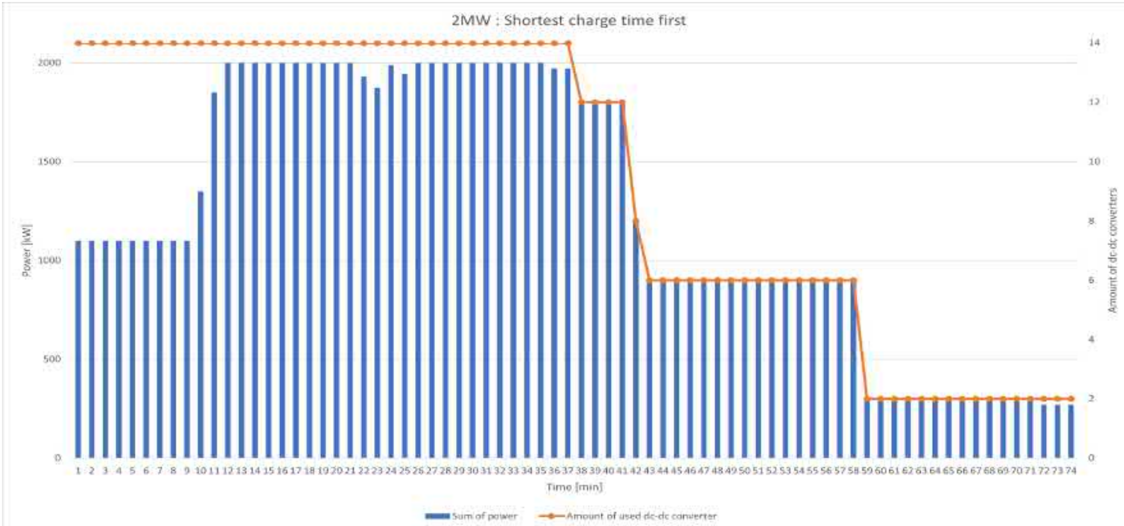

Figure 74: *Shortest charge time first, 1,5MW charger with 150kW converters*

Figure 75: *Shortest charge time first, 2MW charger with 150kW converters*

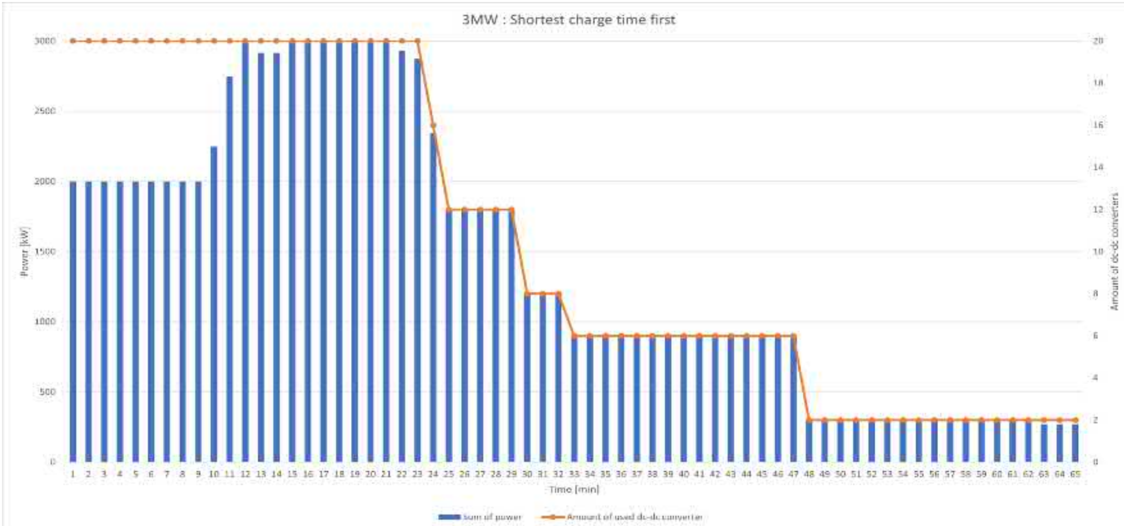

Figure 76: *Shortest charge time first, 3MW charger with 150kW converters*

A.5 200kW DC-DC converter

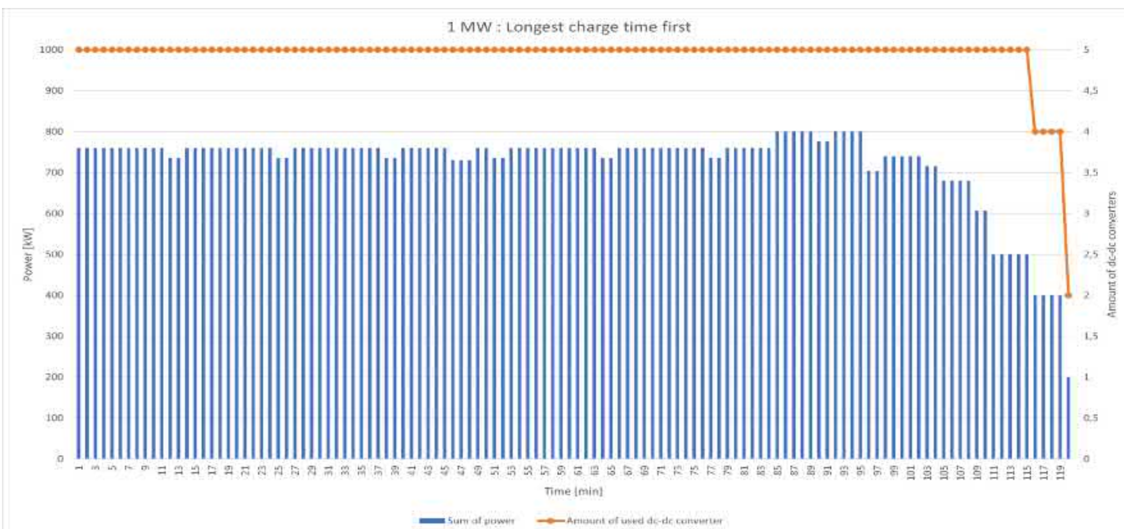

Figure 77: *Longest charge time first, 1MW charger with 200kW converters*

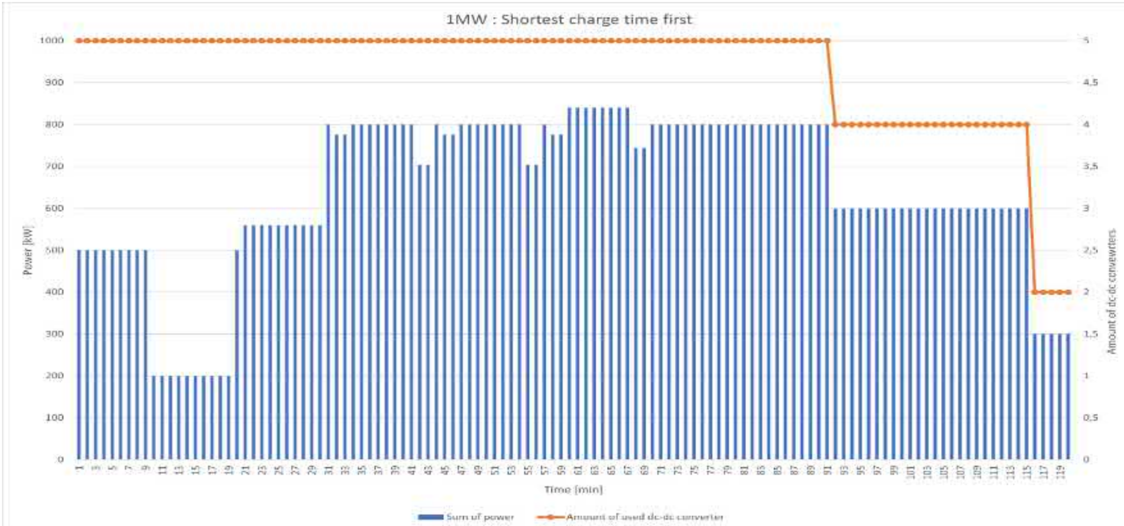

Figure 78: *Longest charge time first, 1.5MW charger with 200kW converters*

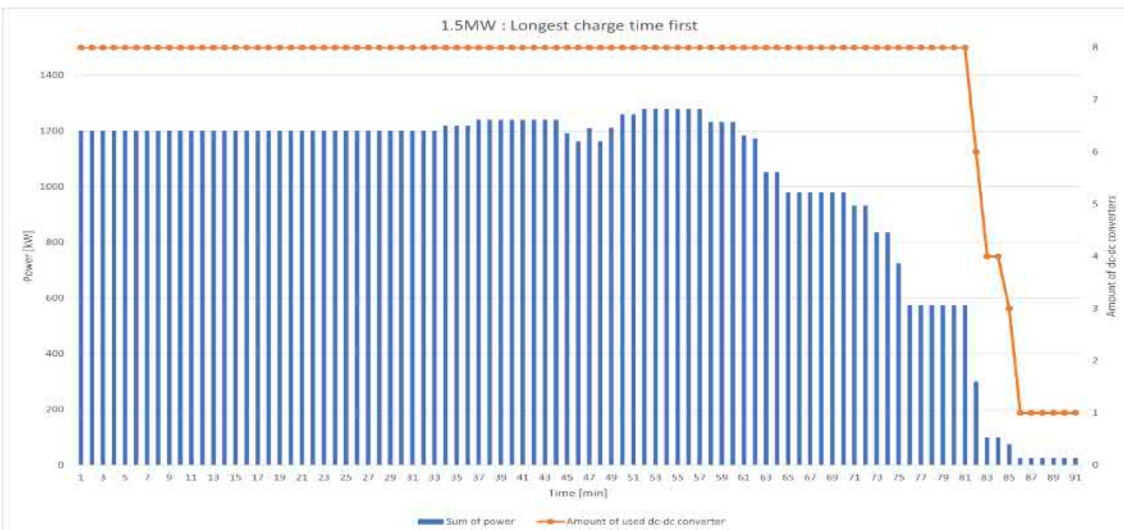

Figure 79: *Longest charge time first, 2MW charger with 200kW converters*

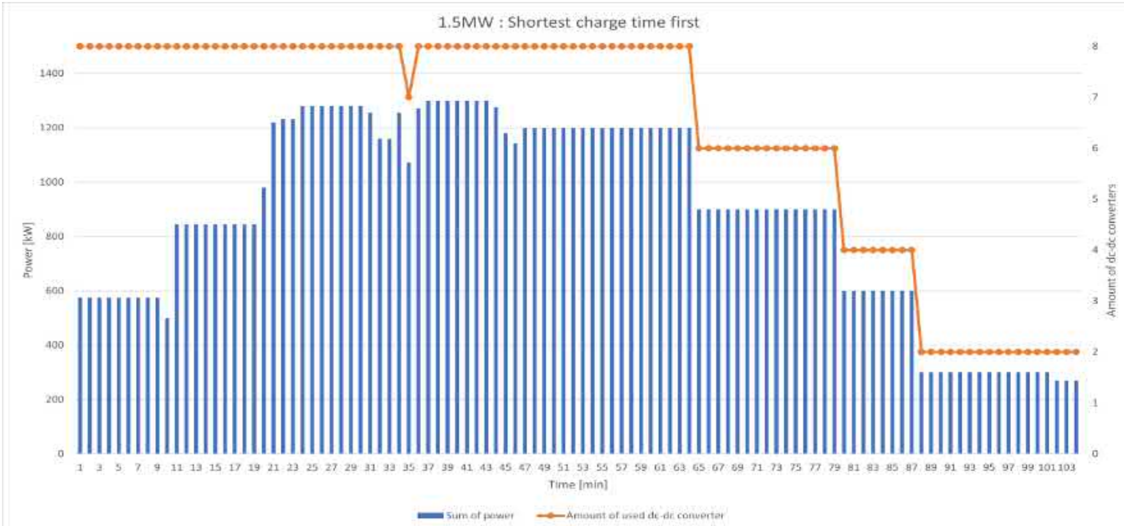

Figure 80: *Longest charge time first, 3MW charger with 200kW converters*

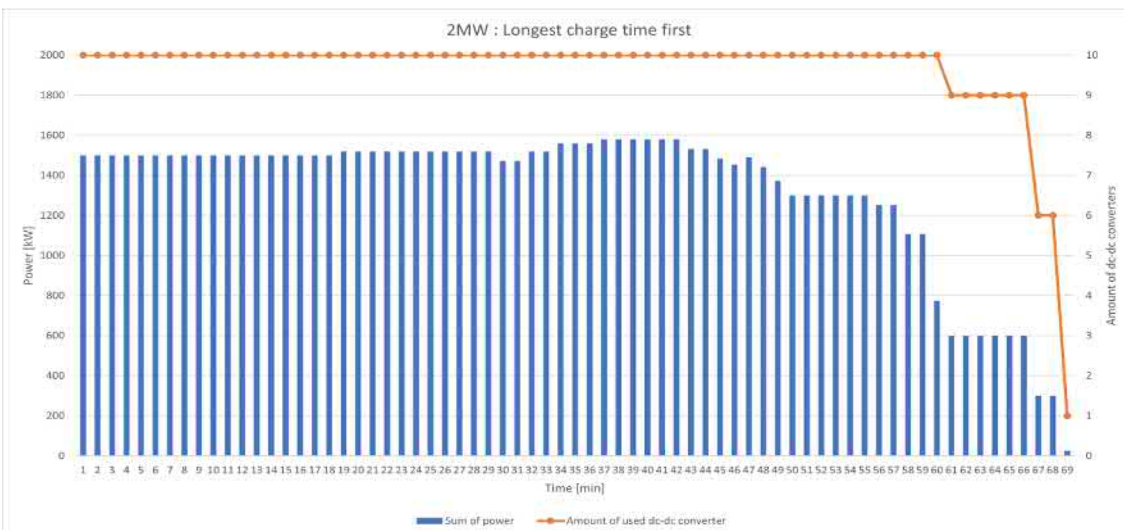

Figure 81: *Shortest charge time first, 1MW charger with 200kW converters*

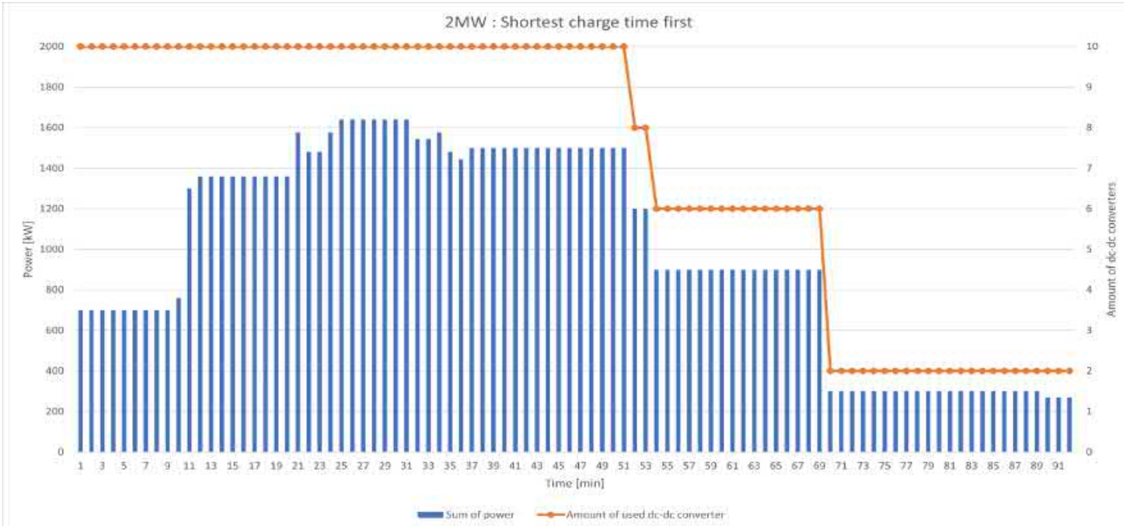

Figure 82: *Shortest charge time first, 1,5MW charger with 200kW converters*

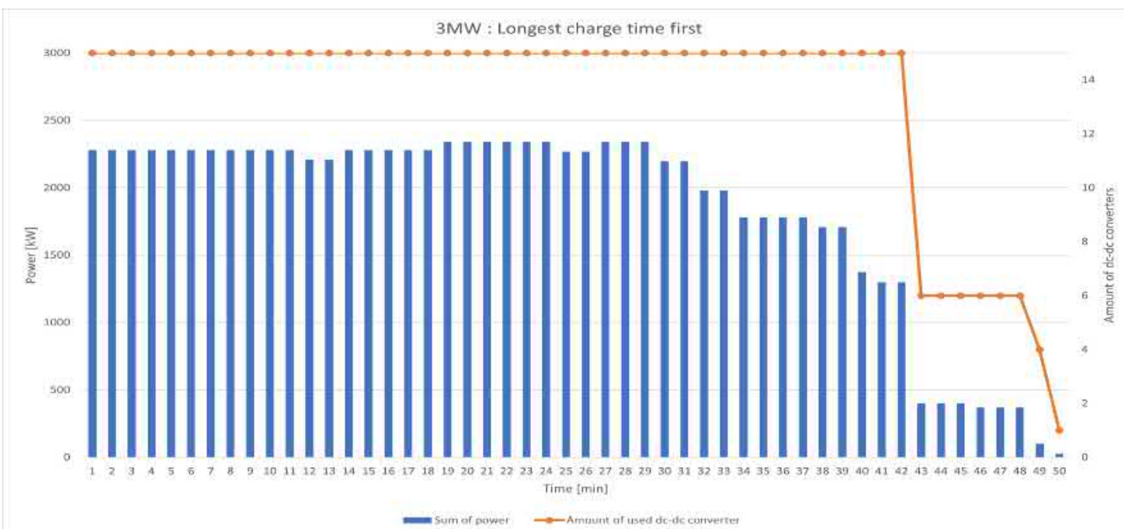

Figure 83: *Shortest charge time first, 2MW charger with 200kW converters*

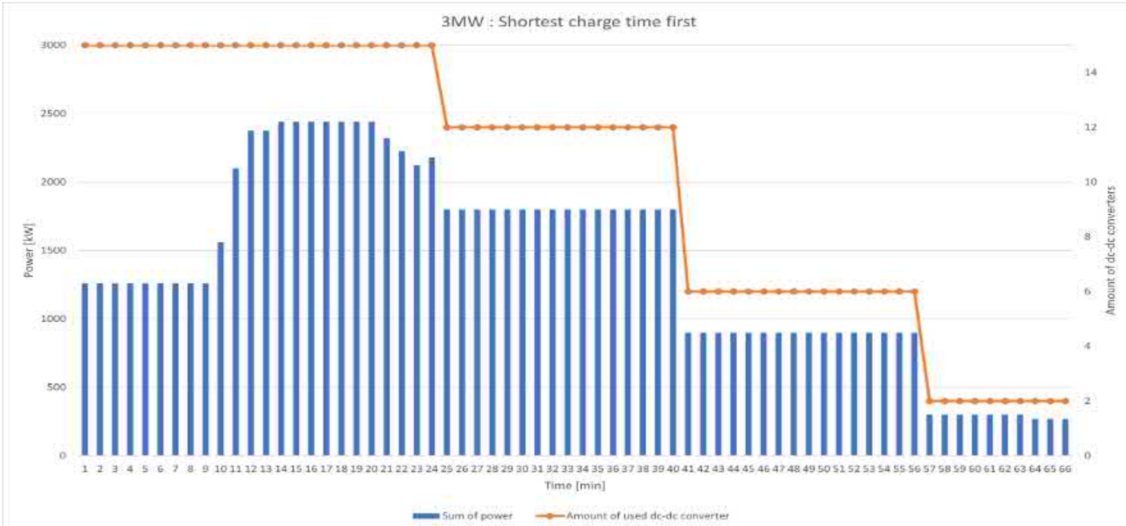

Figure 84: *Shortest charge time first, 3MW charger with 200kW converters*

B Arduino code for contactor control

```
int IN1 = 9; //RY1
int IN2 = 8; //RY2
int IN3 = 7; //RY3
int IN4 = 6; //RY4
int IN5 = 5; //RY5
int IN6 = 4; //RY6
int IN7 = 3; //RY7
int IN8 = 2; //RY8

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);

  //Assigns the pins on the Arduino as outputs
  pinMode(9, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(6, OUTPUT);
```

```
  pinMode(5, OUTPUT);
  pinMode(4, OUTPUT);
  pinMode(3, OUTPUT);
  pinMode(2, OUTPUT);

//TURN OFF RELAYS (in Normaly Open config). The relays are opened at
//the start
  digitalWrite(IN1, LOW);
  digitalWrite(IN2, LOW);
  digitalWrite(IN3, LOW);
  digitalWrite(IN4, LOW);
  digitalWrite(IN5, LOW);
  digitalWrite(IN6, LOW);
  digitalWrite(IN7, LOW);
  digitalWrite(IN8, LOW);


Serial.print("Which converter do you want to connect to which ERS rail: \n ");
Serial.println("C1 to E1: on1");
Serial.println("C1 to E2: on2");
Serial.println("C2 to E1: on3");
Serial.println("C2 to E2: on4");
Serial.println("Turn all off: off");
}

void loop() {
  // put your main code here, to run repeatedly:
  String readString;
  String Q;

  while(Serial.available()){
    delay(1);
    if(Serial.available()){
      char c = Serial.read();
      if(isControl(c)){
```

```
        break;
      }
      readString += c;
    }
  }
  Q = readString;
  if(Q == "on1"){
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, LOW);
    delay(1000);
    digitalWrite(IN1, HIGH);
    digitalWrite(IN2, HIGH);

  }
  if(Q == "on2"){
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, LOW);
    delay(1000);
    digitalWrite(IN3, HIGH);
    digitalWrite(IN4, HIGH);

  }
  if(Q == "on3"){
    digitalWrite(IN7, LOW);
    digitalWrite(IN8, LOW);
    delay(1000);
    digitalWrite(IN5, HIGH);
    digitalWrite(IN6, HIGH);

  }
  if(Q == "on4"){
    digitalWrite(IN5, LOW);
    digitalWrite(IN6, LOW);
    delay(1000);
    digitalWrite(IN7, HIGH);
```

```
    digitalWrite(IN8, HIGH);

  }
  if(Q == "off"){
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, LOW);
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, LOW);
    digitalWrite(IN5, LOW);
    digitalWrite(IN6, LOW);
    digitalWrite(IN7, LOW);
    digitalWrite(IN8, LOW);
  }
  if(Q == "off1"){
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, LOW);
  }
  if(Q == "off2"){
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, LOW);
  }
  if(Q == "off3"){
    digitalWrite(IN5, LOW);
    digitalWrite(IN6, LOW);

  }
  if(Q == "off4"){
    digitalWrite(IN7, LOW);
    digitalWrite(IN8, LOW);
  }
}
```