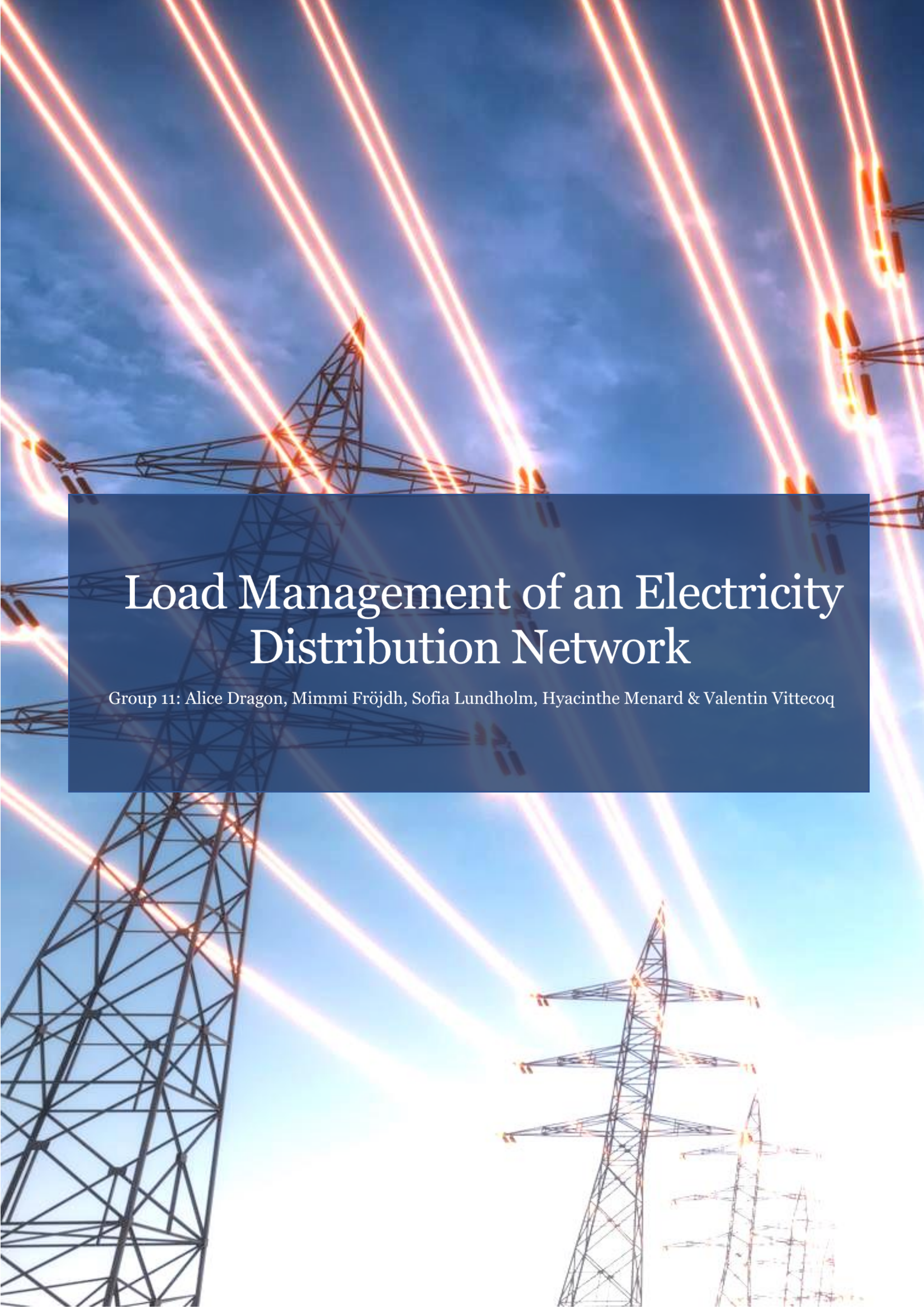


Load Management of an Electricity Distribution Network

Group 11: Alice Dragon, Mimmi Fröjdh, Sofia Lundholm, Hyacinthe Menard & Valentin Vittecoq

Table of content

1 Introduction

1.1 Background

In Sweden, the transport sector is responsible for almost one third of the country's emission of greenhouse gases. The government considers electrification to be an important part of quickly reducing emissions in the sector and they are therefore intensifying their work on electrifying the transport sector (Eneroth, 2021). Electrical vehicles (EV) are already rapidly increasing in Sweden and between the years 2019 to 2022 the number of rechargeable cars has increased by 432 percent (Power Circle, 2022).

The rapid increase of EVs and charging stations fed from the low or medium-voltage distribution network in Sweden creates new technical challenges for the electricity grid. The increasing load from the charging infrastructure can result in negative effects to the electricity grid through decreasing the lifespan of power equipment and overloading the grid and voltage reductions. The transition to electromobility can also lead to a lack of production capacity and congestion of the transmission network during high-load hours. Today, there is a limited amount of research regarding the interaction and compatibility between the electricity grid and charging infrastructure, resulting in insecurities about how much hosting capacity the grid can handle (Bollen & Shimi, 2021). To be able to continue reducing carbon dioxide emissions by the electrification of the transport sector, it is therefore important to better understand the effects of the charging stations to limit the negative consequences on the grid.

1.2 Objectives

The aim of the project is to gain a greater understanding of how the implementation of charging stations can affect an electric grid. To do so, an electric distribution network has been analyzed and optimized with regards to adding new loads in the form of EV chargers. A hypothetical electric grid (the CIGRE network) has been examined, fitted with existing loads, and implemented with new loads in the form of household EVs with reference to a real-life case study of customer load shapes (NREL, 2022).The system was then analyzed based on the following factors: Bus voltages, line loading, and transformer loading. When examining the network in the analysis, the following criteria needs to be fulfilled:

0.9 [pu] ≤ Bus voltage ≤ 1.1 [pu]

Line loading ≤ 100%

Transformer loading ≤ 100%

In section two of the report, the existent network behavior and qualities excluding EVs are analyzed. In the later parts, customer load shapes are included, and the limitation of the system is examined. Issues investigated are: How many EVs can the system handle? When and how is the system overloaded? How can the load management and quality of the grid be improved?

2 The Network in its Original State

2.1 State of the CIGRE Network

Before adding charging stations and load shapes, the original state of the network was examined. It is a medium-voltage CIGRE network that has the following properties:

- 8 switches
- 18 loads
- 1 external grid
- 15 lines
- 2 transformers
- 15 buses

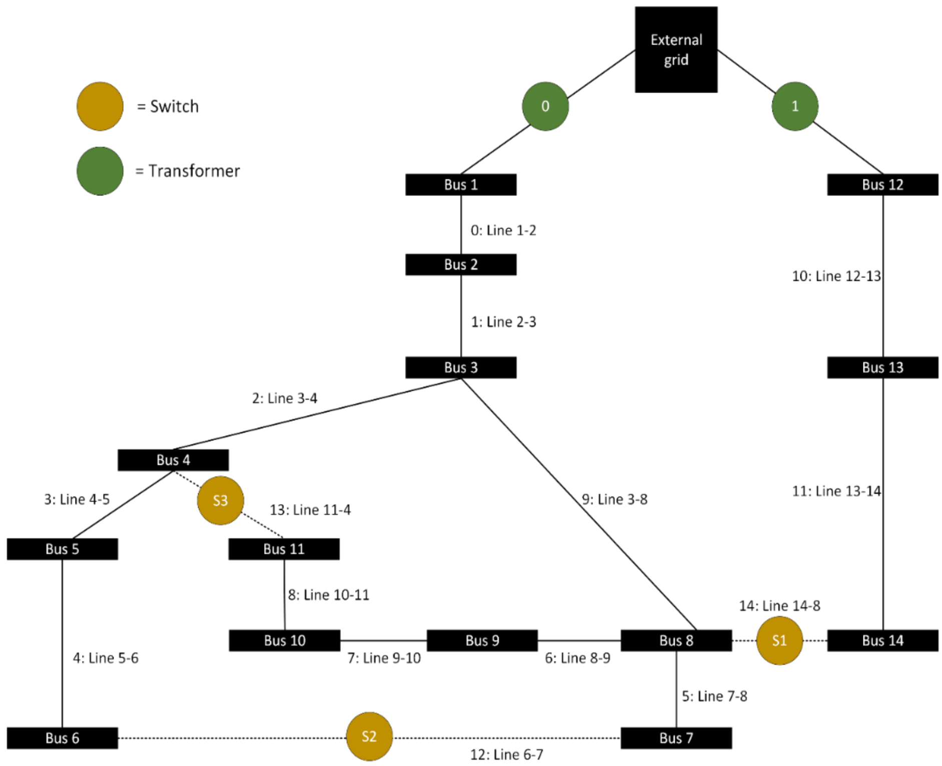


Figure 1: Network properties.

The current state of the bus voltage, line loading and transformer loading is shown in Table 1, Table 2, and Table 3 in Appendix A.

As one can see, all the buses and lines satiate the requirements given (0.9 [pu] ≤ Bus voltage ≤ 1.1 [pu] and Line loading ≤ 100%), although line 0 and line 1 are close to 100%. Transformer 0 does not meet the system requirements since it is loaded over 100%. However, this is an original mistake in the existing network, and it should not be considered as a parameter to define if a line is critical or not when the network is in its original state.

To gain a better understanding of the location of the buses and lines that are close to violating the criteria, the network is illustrated with colors showing the bus voltage and line loading in Figure 2.

One can see that due to the voltage drops at each bus, the buses that are further from the external grid have a lower voltage.

The lines close to the external grid must provide electricity to the whole network and therefore has more power running through them which is why line 0 and 1 are almost loaded to 100 percent. However, line 10 and 11 has lower impedance and capacitance which is why they are not close to the critical limit.

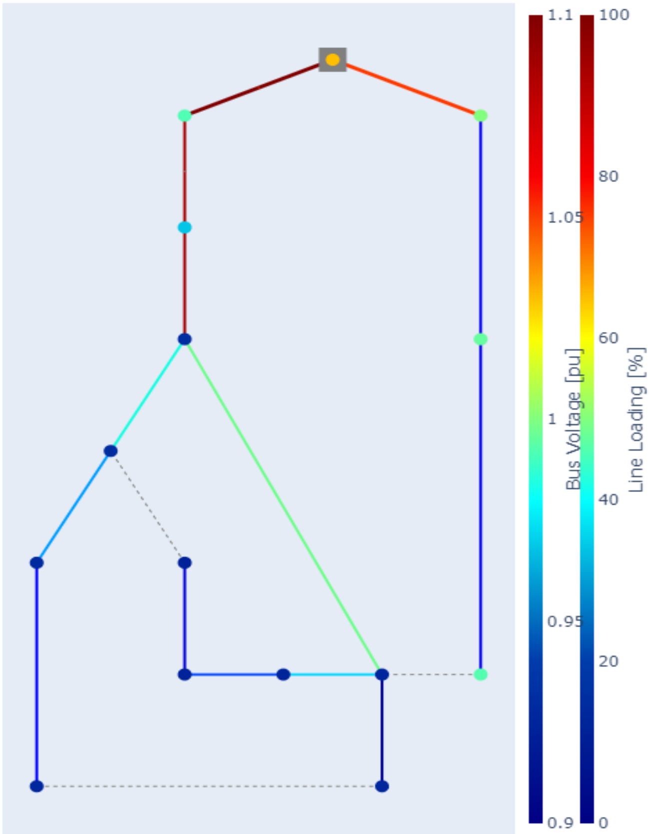


Figure 2: The network with bus voltage and line loading illustrated.

2.2 N-1 Contingency Analysis

In this section, it was observed what happens to the system when performing a (N-1) contingency analysis. When performing this analysis, one line at a time is disconnected to investigate how the rest of the system responds. In this analysis, the criteria's stated in the objective are used. When performing the analysis, different switches are closed for the whole system to get electricity. If two switches could be closed, the best-case scenario was used since the switches can be opened and closed as desired. Which switches are closed when a line is dropped, and which critical situations occur are shown in Table 4.

Lines 12, 13 and 14 are already dropped in the initial network since they contain the opened switches, and they are therefore not critical. The result shows that 4 lines lead to a critical situation when they are disconnected, lines 0, 1, 10 and 11. This is due to all the power coming from the external grid going through these principal lines, bringing electricity to the whole network.

Another method have been tried: it consisted of observing which lines disconnected led to a critical situation, for all the different switch alternatives (no switches open, S1 open, S2 open, S3 open, S1 & S2 open, S1 & S3 open, S1 & S3 open, S1 & S2 & S3 open). Then the results have been analyzed to determine which lines made all switch alternatives fail for one of the critical conditions. This other technique and gave the same result as the first one.

Line dropped	Switch closed	Critical situation
Line 0 dropped	S1	Vm_pu bus 5 = 0.899 pu Vm_pu bus 6 = 0.898 pu
Line 1 dropped	S1	Vm_pu bus 4 = 0.899 pu Vm_pu bus 5 = 0.898 pu Vm_pu bus 6 = 0.896 pu
Line 2 dropped	S2 or S3	No critical situation
Line 3 dropped	S2	No critical situation
Line 4 dropped	S2	No critical situation
Line 5 dropped	S2	No critical situation
Line 6 dropped	S3	No critical situation
Line 7 dropped	S3	No critical situation
Line 8 dropped	S3	No critical situation
Line 9 dropped	S1, S2 or S3	No critical situation
Line 10 dropped	S1	L0 overloaded: 111.812% and L1 overloaded: 112.318%
Line 11 dropped	S1	L0 overloaded: 110.868% and L1 overloaded: 111.372%

Table 4: The switches closed and critical situations that occur when a line is dropped.

2.3 N-1 Contingency Analysis, changing critical conditions

Next, it was examined which critical situations occur in an N-1 contingency, if some of the conditions provided in the objective were changed. For this case, the voltage requirements for the buses were between 0.95 pu and 1.05 pu. The line loading and transformer loading is still considered to be 10%. The result from this analysis is shown in Table 5.

Line dropped	Switch closed	Critical situation
Line 0 dropped	S1	Vm_pu bus 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14 < 0.95 pu
Line 1 dropped	S1	Vm_pu bus 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14 < 0.95 pu
Line 2 dropped	S2 or S3	Vm_pu bus 3, 4, 5, 6, 7, 8, 9, 10, 11 < 0.95 pu
Line 3 dropped	S2	Vm_pu bus 3, 4, 5, 6, 7, 8, 9, 10, 11 < 0.95 pu
Line 4 dropped	S2	Vm_pu bus 3, 4, 5, 7, 8, 9, 10, 11 < 0.95 pu
Line 5 dropped	S2	Vm_pu bus 3, 4, 5, 6, 8, 9, 10, 11 < 0.95 pu
Line 6 dropped	S3	Vm_pu bus 3, 4, 5, 6, 7, 8, 9, 10, 11 < 0.95 pu
Line 7 dropped	S3	Vm_pu bus 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 < 0.95 pu
Line 8 dropped	S3	Vm_pu bus 3, 4, 5, 6, 7, 8, 9, 10, 11 < 0.95 pu
Line 9 dropped	S1, S2 or S3	Vm_pu bus 10, 11 < 0.95 pu
Line 10 dropped	S1	Line 0 overloaded: 111.812 %, Line 1 overloaded: 112.318 % Vm_pu bus 3, 4, 5, 6, 8, 9, 10, 11, 13, 14 < 0.95 pu
Line 11 dropped	S1	Line 0 overloaded: 110.868%, Line 1 overloaded: 111.372% Vm_pu bus 3, 4, 5, 6, 8, 9, 10, 11, 14 < 0.95 pu

Table 5: Critical situations that occur when a line is dropped with changed conditions.

With the new conditions, all the lines including line 12, 13 and 14 are critical since critical situations occur even before a line is dropped. In the original network, busses 3 to 11 already have a voltage below 0.95 pu.

3 Implementation of Charging Stations and Load Shape

After the examination of the existent network, the original characteristics were changed. Firstly, 5 new charging stations were added to the system. To do so, 5 new low voltage buses (at 0.4 kV) and 5 transformers 20kV to 0.4kV were created. The transformers were placed on bus 2, 4, 6, 12 and 14 to be evenly distributed across the network to provide people with a charging station always close by. The transformer with more rated apparent power was chosen to provide more capacity to host loads (0.63 MVA 20/0.4 kV). This choice was made to intent that the capacity of the transformer will not limit the number of EVs that can be connected to the network in the next step. This way, the critical limits of the lines could be better examined.

Now the network has the following properties, visible on Figure 3:

- 8 switches
- 18 loads
- 1 external grid
- 15 lines
- 7 transformers
- 20 buses, including CS1, CS2, CS3, CS4, CS5 for the charging stations

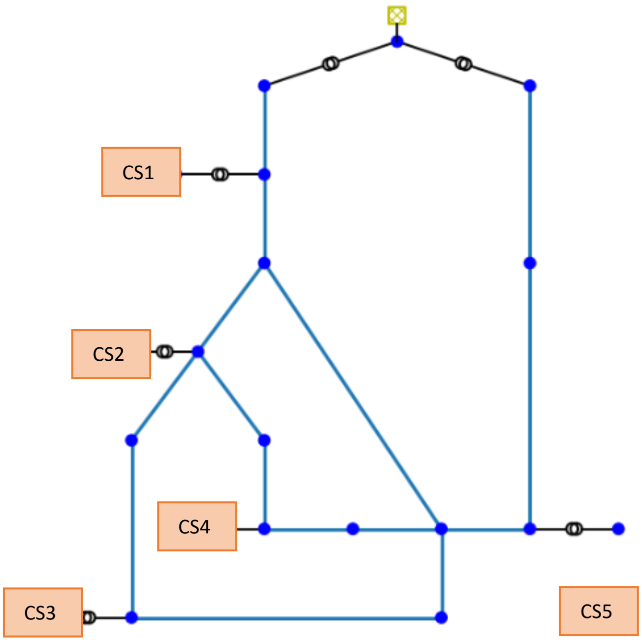


Figure 3: New network, including 5 charging stations

The given load shape of the existent 18 customers was also added, so that the loads are not constant anymore. The load shape is shown in figure 4.

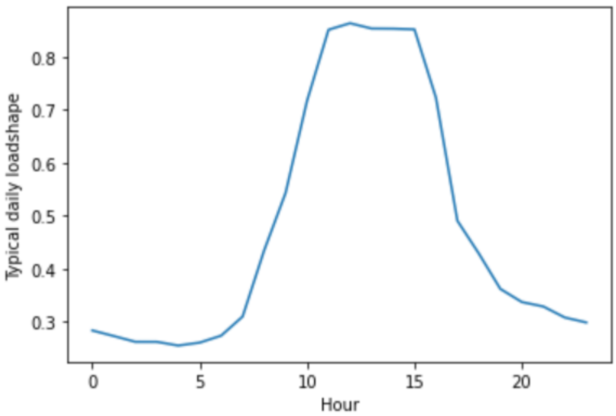


Figure 4: Load shape of the existent customers.

In Figure 4, one can see that the load on the network increases between 7am and 18pm and is constant between 11 am and 3 pm. During the night and early morning there is almost no load. From this load shape, it can be concluded that the consumption presumable is connected to an industrial or office area, where the electricity is consumed when people come to work.

Next, the time series created from the load shape was ran in Panda Power and the network was examined based on characteristics provided by the code in Excel. When the load shape and empty charging stations are added, the network is always less loaded than in the first step. The maximum line loading is now 82,21% in line 1 at 12 am which can be compared to the maximum line loading of 96.96% in line 1 in the original state of the network. Moreover, the bus voltage is also improved and all the vm_pu are between 0.94 and 1.03 whereas in Step 1, they could drop to 0.92.

In conclusion, compared to step 1, the network is in a better state. The explanation is that in step 1, a static load was used whereas in step 2, with the load shape added only a fraction (<100%) of this load is applied which reduces the power in the lines. Furthermore, the load from EVs recharging on the system is yet not added so there is no new load in the network. In the next step, the loads from EVs are added and the new state of the network is examined.

4 EV Recharging on the System

4.1 Allocate a chosen number of EVs

Next, the EVs were allocated to recharge in the system which add an additional load shape to the one of the 18 customers. The loads from the EVs are taken from a real-life case study of customer load shapes (NREL, 2022). Figure 5 shows 3 examples of charging profiles that are used. At any point, each vehicle is either charging with a charging power of 6600W or not charging. One can also notice that not all vehicles are charging at the same time and that each vehicle is only charging for a short period of the day.

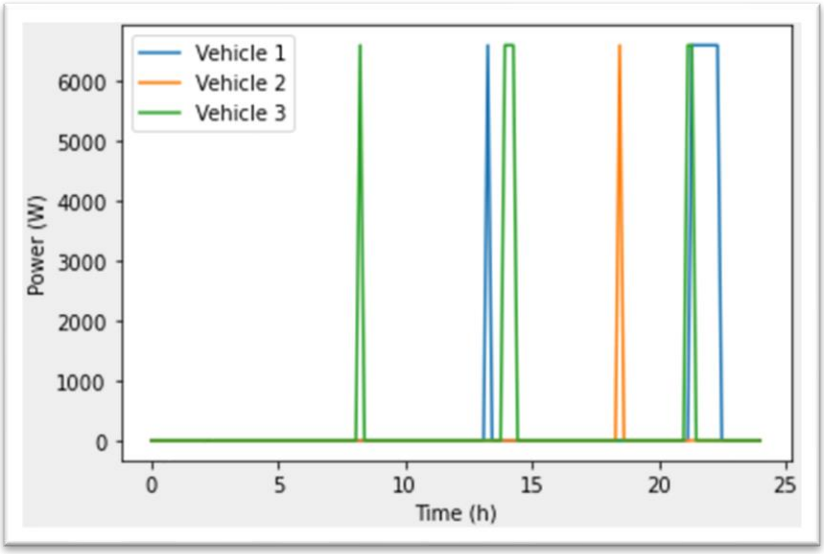


Figure 5: Example of 3 charging profiles from the NREL data

Figure 6 shows the average total charging power of all the 348 vehicles from the Excel file given, during the year.

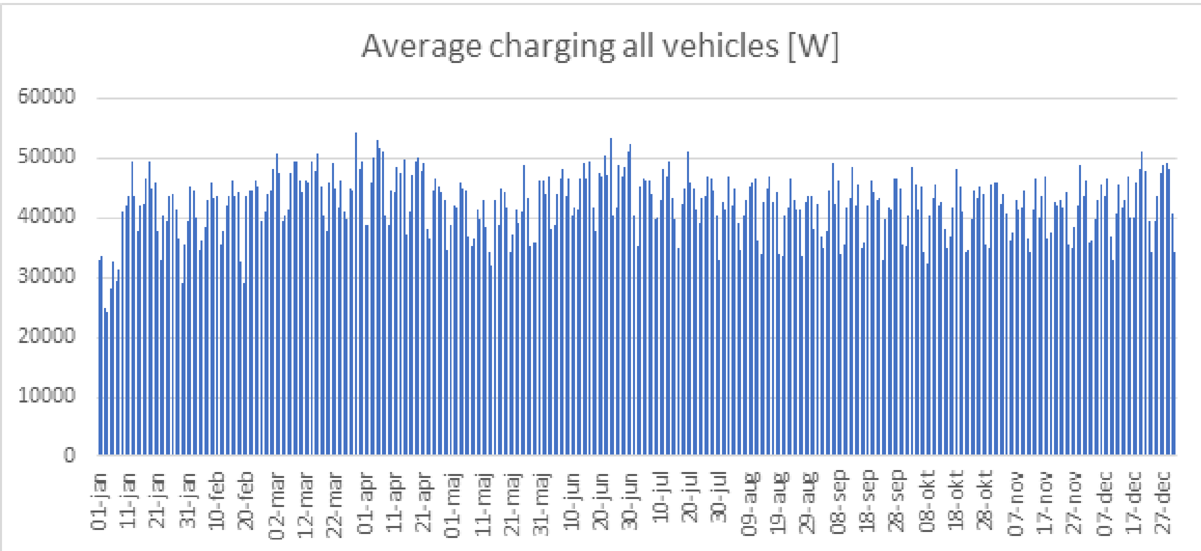


Figure 6: Average over each day of total charging power of all 348 vehicles [W]

As one can see in Figure 6, the charging of the vehicles differs from day to day but stays relatively constant between the different months. Since the amount of data was so large, the data from different randomly chosen days were used when adding the load to the network.

In this analysis, charging losses and inductive losses are not taken into consideration and the power factor for the chargers was set to 0. When investigating how many of the vehicles connected to the system were charging at the same time, it was found that less than 18 percent of the fleet was charging at the same time. Moreover, the vehicles were mostly recharged during the day between 10 AM and 12 PM.

Figure 7 shows the percentage of the fleet charging at the same time and the average percentage of vehicles charging over one day.

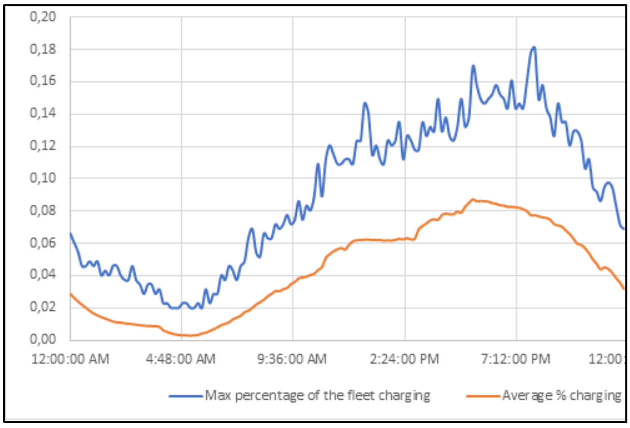


Figure 7: Percent of the fleet charging.

The two load shapes from Figure 7 are defined as follow:

Average charging [time] = $\sum_{i=1}^{365} \%\ charging\ day_i\ /365$

Max charging [time] = MAX(% charging day$_i$)

To begin and analyze the consequences of adding a vehicles fleet to the network, 100 electric vehicles were randomly chosen on each charging station. This result in a total of 500 different EVs in total, each following a different charging profile over a day. In the data from NREL, the first 100 vehicles were chosen on 5 randomly chosen days. The 100 different profiles were summed to allocate the total load on each charging station.

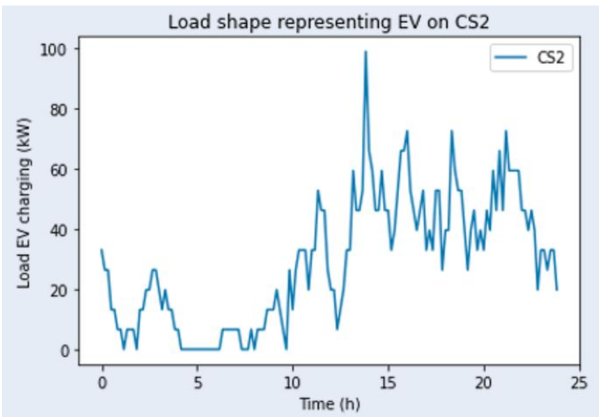


Figure 8: Total load shape on CS2 with 100 EVs

Figure 8 shows the total load applied on charging station 2 over one day, from the sum of 100 different profiles. Here it can be noticed that:

- Most of the vehicles are charging during the day, and almost no vehicles during the night.
- The maximum load is 100 kW. Since the power of one charger is 6.6kW, this means that at any time less than 15 vehicles over 100 are charging, the station thus needs 15 plugs only to power a fleet of 100 vehicles.

The network was then analyzed considering the load shapes of the consumers and of the EVs. Figure 9 shows the state of the network at 12:50, which is the time when line L0 is the most loaded. At this time, line L0 is loaded at 86.1%, which is more than in the previous scenario with no EVs (82%), but still not critical. It is therefore possible to add even more vehicles.

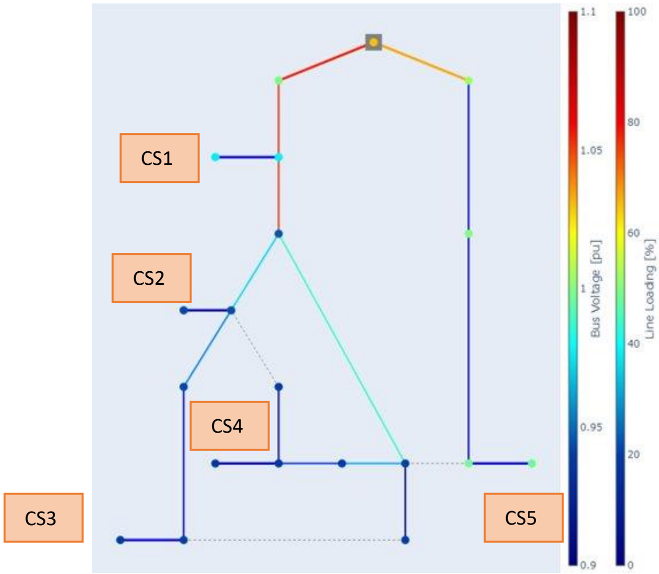
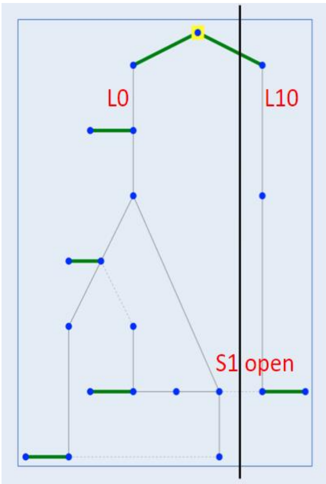


Figure 9: State of the network at 12:50 (max loading of L0) with 100 EVs on each CS

4.2 Find the maximum number of EVs

In this step, the number of EVs the network can host without exceeding its limits are found. To find this limit, the number of vehicles on each CS is increased until the network became overloaded. In the code, it was easy to modify the number of vehicles on each charging station and the corresponding loads were modified accordingly. The load applied on each charging station is simply changed by summing a different number of recharging profiles.

Before trying random numbers of vehicles in the fleet, the maximum number of EVs in the total fleet that the network could sustain was estimated. Previously, it was seen that with 100 EVs on each CS, the network was not overloaded and the most loaded line L0 was only loaded at 86.1% at 12:50 which is only 4 percent more than the scenario with no EVs. The network should therefore be able to host a fleet at least 4 times larger. If the network is analysed in normal conditions, a more precise approximation can be found; under normal conditions (when no line is dropped), the left and right side of the network are independent as S1 is opened. The right and left side of the network can therefore be independently analysed. From this point, EVs are evenly distributed on the left side and the fleet relying on CS5 is independent (Figure 10)



On each side of the network, either the heading line or the transformer will limit the maximum number of vehicles charging. To understand what will limit the fleet size, it must be found what will be failing first on each side when more EVs are added. The limit for each component was therefore estimated.

Figure 10: The two sides of the network

- **Transformer's limit:**

The transformer's limit is determined with its rated power:

Rated power of the transformer P-trafo (MVA)	**Max number of vehicle charging at the same time to not overload the transformer**	**Corresponding Nb of vehicle in the fleet (assumed that a maximum of 18% of the fleet is recharging)**
0.25	37	205
0.4	60	333
0.63	95	527

Table 6: Critical number of vehicles in the fleet depending on the size of the transformer.

Each transformer has its own fleet (as vehicle are associated to a single charging station). Table 6 shows the critical number of vehicles charging at the same time in relation to the size of the transformer. The table also presents the corresponding size of the fleet if 18 percent of the vehicles are recharging (it is a conservative choice with the observed maximum in figure 7). These results can help to better size the transformers to avoid additional costs with unnecessary extra power.

- **Line's limit:**

As the lines have the same characteristics, the first line that will fail will be the heading line since the power of all loads below pass through this line. On each side, the heading line is always the more loaded. The line's limit is then calculated for each side based on the additional load from EV the heading line can sustains.

To determine the maximum number of vehicles that could be plugged at the same time on each side the results from step 1 were used, as shown below for the left side.

An equivalent load below each heading line is first calculated:

From step 1 results:

Line loading [%]	
0: Line 1-2	96.482

	p_from_mw	q_from_mvar	p_to_mw	q_to_mvar
0	4.548928e+00	1.504345	-4.466243e+00	-1.437640e+00

The total equivalent load under the line is then equal to:

$$S_{toL0,Step1} = \sqrt{{p_{toL0}}^2 + {q_{toL0}}^2} = 4.69\ MW$$

The maximal acceptable load for L0 is then determined:

$$Max\_load\_L0 = \frac{S_{toL0,Step1}}{L0\_load, step1} = \frac{4.6919}{0.9648} = 4.86\ MW$$

With this maximal load one can determine the available load on L0 for the EV depending on the consumers' loads.

- **Limit for the left side of the network:**

In the previous step it was seen that L0 was the most critical and the first to become overloaded. This line will also be the first failing when more vehicles are added on CS1, CS2, CS3, CS4. The maximum number of vehicles that could be connected to the left side of the grid was therefore found through calculating the load that can be added before exceeding the limits of the line.

After the Charging Stations implementation and with the load shape for the existent loads, the line loading can be computed the as a function of the time (results from step 2). With the new max loading percent found at 12 PM: 81.78% (figure 11).

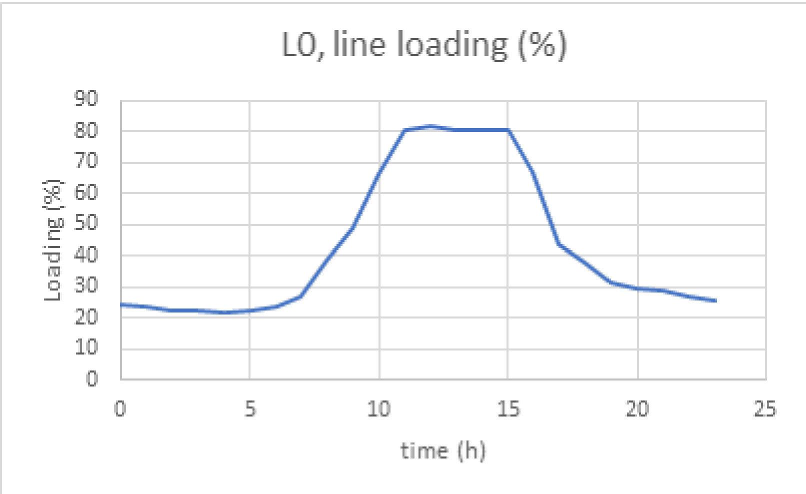


Figure 11: Line loading for L0 as a function of time

Considering the maximal load acceptable for L0, the maximum number of vehicles that can charge (on CS1-CS4) without exceeding the limit for L1 can now be calculated. This max additional load is time dependent with loads from consumers:

$$Max\_charging\_vehicle(t) = Max\_load\_L0.(1 - loading(t))/P\_vehicle$$

$$Max\_charging\_vehicle(t = 12\ PM) = 4.8631 * (1 - 0.8177)/0.0066 = 134$$

With this load shape for consumer loads, 134 EVs will be the limit for 12 PM (this is the sum for CS1 – CS4) but the grid could support more vehicle charging at the same time at other times of the day. If the same calculation are performed for each hour of the day, the following curve is found (figure 12):

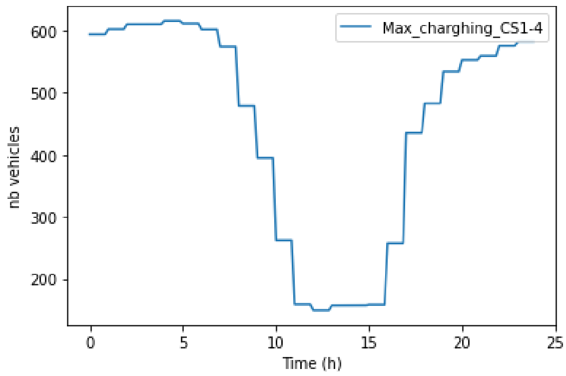


Figure 12: Maximum number of EVs recharging on CS1-4 as a function of time

The limit for EVs is as expected time dependent, 600 vehicles could be plugged at midnight but only 134 at noon. By increasing the number of vehicles on CS1-4 this limit has been reached for 418 vehicles:

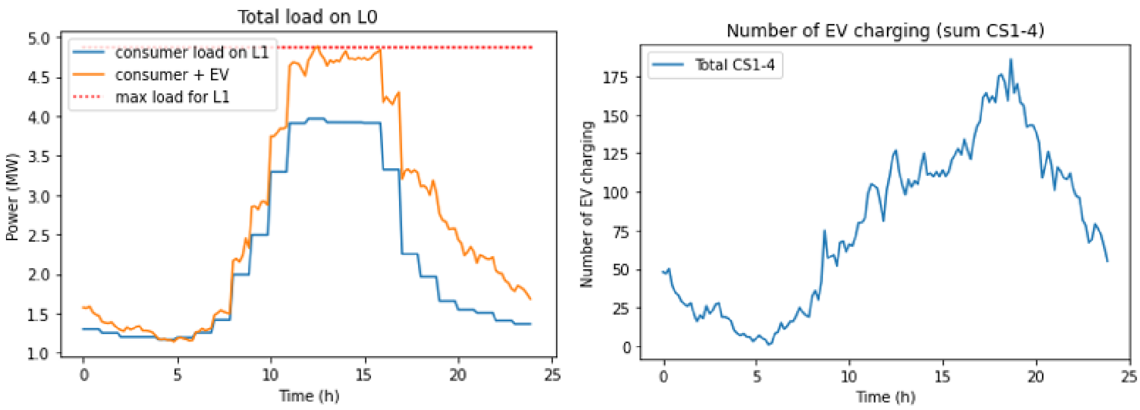


Figure 13: Total load on L0 and number of EVs as depending on the time

Figure 13 shows that in this new configuration (418 EVs on each CS from the left side), the line limit is reached at 12AM with 125 EV charging on CS1-4. This is less than the limit of 134 calculated above, however, in the calculations electrical losses are neglected. A maximum of 180 vehicles recharging simultaneously at 6 PM which gives an average of 45 EVs per station at 6 PM, so with results from table 6 transformers on the left side could be downgraded to the **medium size**.

- **Limit for the right side of the network:**

Step 2 shown that the line L10 was not very loaded, so on the right side, the transformer CS5 will limit the number of vehicles charging at the same time. With the transformer selected, the maximum number of EV charging at the same time to not overload the transformer is around 95 with the results from table 6.

By increasing the number of vehicles on CS5 this limit has been reached for 683 vehicles relying on CS5. The following curve (figure 14) shows the number of vehicles in this fleet that are charging at any time during the day.

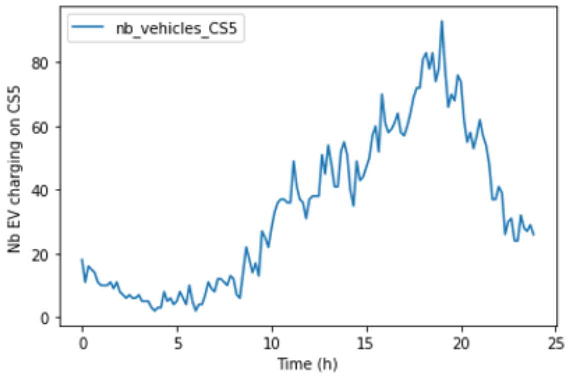


Figure 14: Total load on L0 and number of EVs as depending on the time

In this maximum configuration, this limit is reached on CS5 with 91 EV charging at 6 PM. It is less than the estimation found, however electrical losses were neglected. That is why the network cannot sustain more than 683 EVs on CS5. Again, one can notice that only a small part of the fleet is charging at se same time, in this case a maximum of 13.3% of the fleet is charging.

- **Results for this maximum configuration:**

Finally, it has been found that the network could host a total fleet of 2355 vehicles without exceeding its limits. Of course, as the loads added depend on the recharging profile of the vehicles selected, the result depends heavily on the profiles chosen from the data. In this case, the limit of the network has been reached with 418 EVs on CS1, CS2, CS3, CS4 and 683 EVs on CS5.

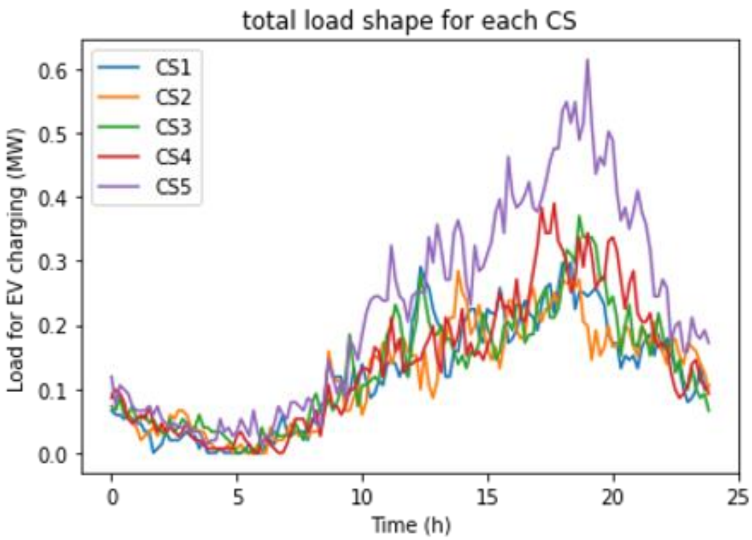


Figure 15: Total load shape for each charging station

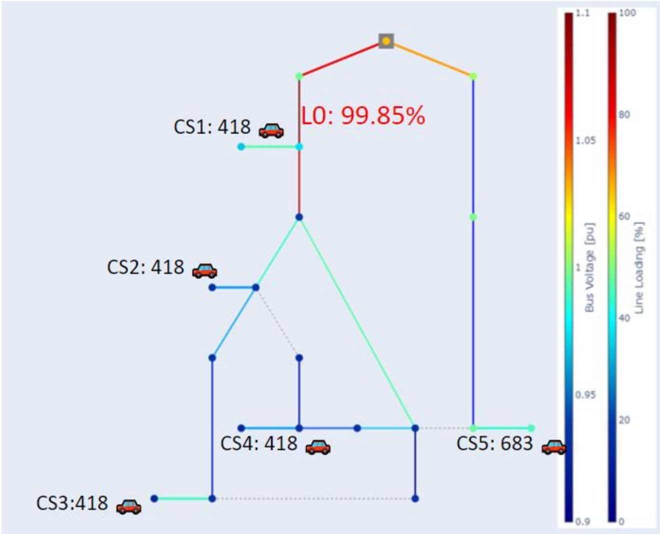


Figure 16: State of the network at 12:50 with the max number of EVs the network can sustain

On figure 15 the corresponding load shape for each charging station in this configuration are presented. The state of the network at 12:50 is presented on figure 16. This time of the day is the most critical as line L0 is close to its limit (L0 loaded at 99,85%). It is therefore not possible to add more vehicles in the network.

4.3 N-1 Contingency Analysis

It was then studied if the network containing the maximum number of EVs can sustain a N-1 contingency analysis. Rather than running a N-1 analysis on every timestep of the previous time series, the most critical element of the network is considered which is L0. Therefore, the N-1 analysis is only performed at the timestep where the load on this line the highest. As concluded in section 4.2, it is at the time 12:50 that the load on L0 is the highest. The figure 16 shows the state of the network for this timestep: L0 is loaded at 99.85%. The result from the N-1 analysis at 12:50 is shown in Table 7.

Line dropped	Switch closed	Critical situation
Line 0 dropped	S1	Buses 6, 15, CS2, CS3: Vm_pu < 0.90 pu
Line 1 dropped	S1	Vm_pu bus CS3 = 0.898 pu
Line 2 dropped	S2 or S3	L0 overloaded: 100.93%
Line 3 dropped	S2	L0 overloaded: 100.42%
Line 4 dropped	S2	L0 overloaded: 100.17%
Line 5 dropped	S2	L0 overloaded: 100.05%
Line 6 dropped	S3	No critical situation
Line 7 dropped	S3	No critical situation
Line 8 dropped	S3	No critical situation
Line 9 dropped	S1, S2 or S3	No critical situation
Line 10 dropped	S1	L0 overloaded: 118.67% and L1 overloaded: 113.65%
Line 11 dropped	S1	L0 overloaded: 117.87% and L1 overloaded: 112.85%

Table 7: The switches closed and critical situations that occur when a line is dropped (N-1 analysis on the time step 12:50).

In the same way as in section 2 of the report, the best-case scenario is used when two switches can be closed. One example is that when line 9 is dropped, any of the tree switches can be closed to provide the whole network with electricity. However, the network will be in a critical situation if switch S2 or S3 are closed but not if switch S1 is closed, thus the best-case scenario is used and line 9 is not considered to be critical. From this analysis it can be noticed that:

- Line 0 and line 1 are critical because if one these lines is dropped, S1 is closed and the power needs to travel by line 10 all the way to the charging station 3, resulting in a voltage drop
- Lines 2, 3, 4, and 5 are critical because when any of these lines is dropped, the power needs to travel a longer way to reach CS2 or CS3, resulting in higher losses and thus to slightly overload line 0
- The most critical lines are lines 10 and 11, because when one of these lines are dropped, lines 0 and 1 need to provide power for all the charging stations, including CS5 which has the highest number of vehicles. However, lines 0 and 1 were already almost loaded to 100 % so they cannot sustain the extra power.

4.4 Reduce the number of EVs to no violation in the N-1 Case

The maximum number of EVs the network can sustains to not have critical line in the N-1 contingency analysis was determined in this step.

The previous N-1 analysis conducted in previous step concluded that the most critical lines were lines 10 and 11 because lines 0 and 1 could not feed the whole network when switch 1 is closed. To not have these critical situations, the number of EVs in the fleet was then reduced until line L0 could power the whole network in this setup.

Figures 17 shows the state of L0 when switch 1 is closed. The new max additional load available for EVs in the grid is much less important since the line must first supply energy to the loads on bus 13 and 14.

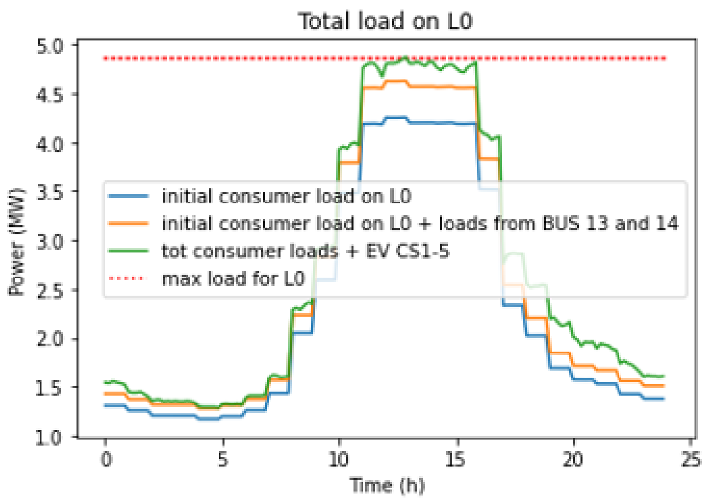


Figure 17: Total load on L0 when S1 is closed and when 95 EVs are allocated on each charging station.

In this case it has been found that the network could only supports 95 vehicles on each CS so a total fleet of 475 EV which only represents 20% of the previous maximum. The state of the network is presented below on figure 18 one can sees that no line is overloaded, and no bus voltage is under 0.9 vm_pu.

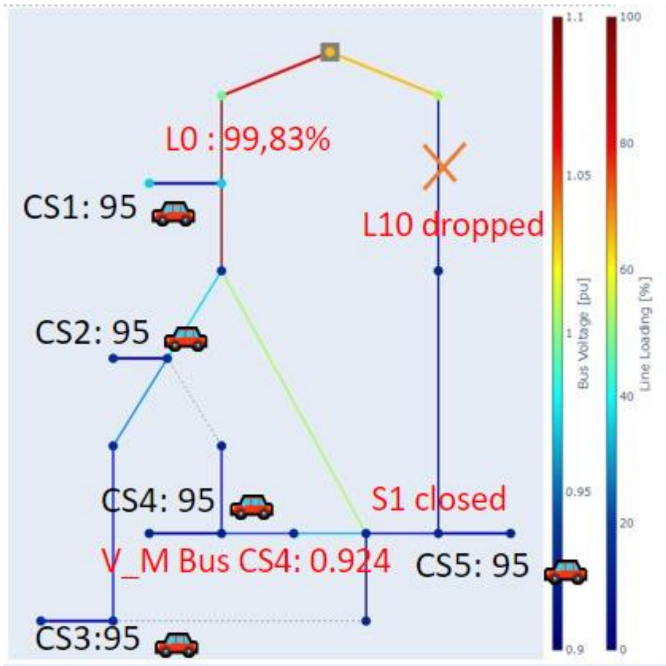


Figure 18: State of the network at 12 AM when S1 is closed and when 95 EVs are allocated on each charging station.

In addition, other lines that were previously critical are no longer critical; lines 0 and 1 were critical because of too much voltage drop but these losses were slightly reduced with the number of EVs. With this configuration, there is no critical line during the N-1 contingency analysis and the network is more reliable and resilient.

5 Sensitivity Studies

In this last part, it was investigated what needs to be done for the network to host 115% of the maximal number of EVs found in section 4 of the report. Since the maximum number of EVs was found to be 490, the system now must be able to host 564 EVs. This could be achieved in many ways, below two different solutions for increasing the host capacity for the EVs are presented.

Firstly, line 0 and 1 were renovated by replacing their characteristics by the ones of lines 10. The features of the cable represented by line 10 is stronger in many ways – it has lower impedance and capacitance, as well as a higher value of the maximum current able to flow through it. These features contribute to the line being able to carry a larger load.

In the other solution, a parallel line was added next to line 0 and 1, which has the same characteristics as the original lines. This splits the power flow in two, roughly halving the load on each parallel connection. This solution is likely cheaper than switching an entire line and replacing it with a higher-capacity line, and it also adds the extra benefit of having more security in the system – if one of the parallel connections breaks, the other lines can deliver power to the network.

Only the number of chargers to the left in the system can be increased due to the transformer sizes, since the transformer to the right already has the maximum transformer size and maximum load from the previous step. The left transformers also need to be larger than the medium size (that was enough in part 4.2), to increase the load with 15%, which was the task of this step. Either the medium or largest size of the transformer can be used for the left transformer – the largest one is implemented in step 3, but the medium size could still be used and fall within the stability requirements of the system. This would also save costs for the network provider, which is important to keep in mind.

Figure 19 shows that the network is not in a critical state, even with 115% of the maximal number of EV found before. The largest line loading on L0 was roughly 49,7% in the chosen solution, which is option 2 – implementing a parallel connection. This equivalent load for step 3 was 99,85%. Since the maximum load of the entire system is on L0, many more EVs than just 115% of step 3 can be added.

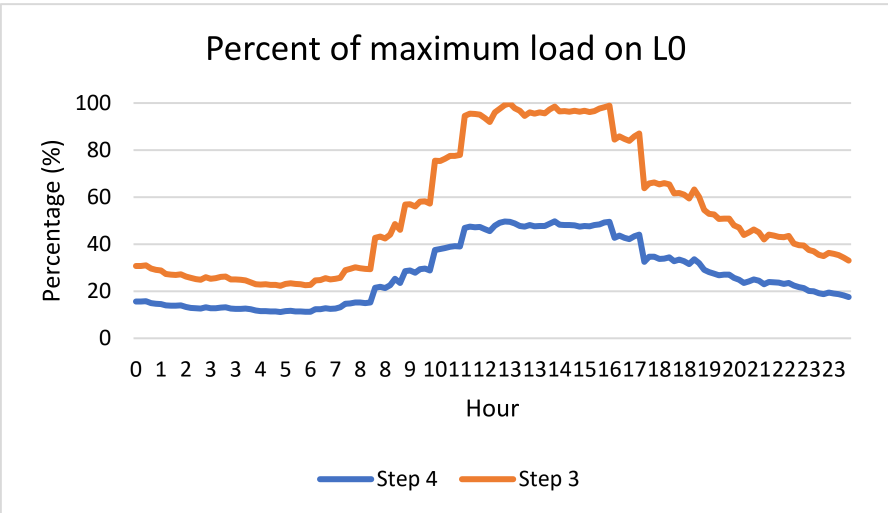


Figure 19: Comparison of the loading of LO

Yet, another solution could have been chosen by implementing smart charging. The potential for this solution in the network is high, since the load profile is very uneven – many consumers are charging around peak hours, and then the load is nearly zero at other times, mainly outside of the evening. This means that a significant amount of the load could be shifted to less load-intensive hours, without the added cost of having to switch cables or use larger transformers than necessary. However, since the area is an industrial or office area, it could be difficult to shift a considerable part of the load since the people are only there working during the day.

6 Discussion and Conclusion

The applied solutions depend on the stakeholders of the investment, the scale of the problem, reliability, operational complexity, and many other factors. For example, Svenska Kraftnät (SVK) are changing the high-voltage transmission lines between Northern and Southern Sweden (Svenska Kraftnät, 2021), one of the biggest reasons being projected increases in demand from electrification in Southern Sweden, for example from EVs. In this large-scale power system with an anticipated rapid increase in energy demand, this investment is worth it to the stakeholders. Smart charging, or load shifting in general, is a lot cheaper for the utility, but it is also less reliable to depend on customers using smart charging and avoiding peak demand. In case of an event where more customers than expected happen to charge at the same time, the network should still hold – there is therefore a trade-off between not under-dimensioning or over-dimensioning the system. There should not be unnecessary costs, however the network should be stable and able to handle a contingency case. Another aspect worth mentioning is that although electricity usually has quite an inflexible elasticity of demand (Csereklyei, 2020), the recent energy crisis might change this behavior, and more consumers might be interested in applying smart energy solutions.

Lastly, the result from the optimization shows that over 15 precent more vehicles can be fitted into the system by adding parallel L0 and L1 lines, ultimately being able to charge more than 564 EVs from a previous maximum of about 490 vehicles.

References

Bollen, Math & Letha, Shimi. 2021. *Impact of electric vehicle charging on the power grid.* Swedish Energy Agency. Available at: https://www.divaportal.org/smash/get/diva2:1530550/FULLTEXT02.pdf [Accessed: 2022-10-17]

Csereklyei, Zsuzsanna. 2020. *Price and income elasticities of residential and industrial electricity demand in the European Union.* Energy Policy, 111079.

Eneroth, Tomas. 2021. T*ransportsektorn elektrifieras*. Regeringskansliet. Available at: https://www.regeringen.se/regeringens-politik/transportsektorn-elektrifieras/ [Accessed: 2022-10-17]

NREL. 2022. *Impact of uncoordinated plug-in electric vehicle charging on residential power demand - supplementary data*. https://data.nrel.gov/submissions/69 [Accessed: 2022-10-02]

Power Circle. 2022. *Elbilsstatistik*. Available at: https://www.elbilsstatistik.se/elbilsstatistik [Accessed: 2022-10-17]

Svenska Kraftnät. 2021. *Nordsyd*. Available at: https://www.svk.se/nordsyd [Accessed: 2022-10-24]

Appendix

Appendix A: Original network characteristics

Bus voltage vm [pu]	
Bus 0	1.03
Bus 1	0.991972
Bus 2	0.968147
Bus 3	0.930961
Bus 4	0.929098
Bus 5	0.927823
Bus 6	0.926321
Bus 7	0.925122
Bus 8	0.925404
Bus 9	0.924422
Bus 10	0.923174
Bus 11	0.922980
Bus 12	1.000146
Bus 13	0.995326
Bus 14	0.992553

Table 1: Bus vm.

Line loading [%]	
0: Line 1-2	96.482978
1: Line 2-3	96.958807
2: Line 3-4	37.580668
3: Line 4-5	28.091021
4: Line 5-6	12.122901
5: Line 7-8	1.936801
6: Line 8-9	33.550914
7: Line 9-10	19.476278
8: Line 10-11	7.294089
9: Line 3-8	48.143637
10: Line 12-13	9.476242
11: Line 13-14	8.908939
12: Line 6-7	0.084082
13: Line 11-4	0.171049
14: Line 14-8	0.037287

Table 2: Line loading.

Transformer loading [%] (net.res_trafo.loading_percent)	
0	101.411473
1	84.698048

Table 3: Transformer loading.