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## Hosting Capacity of the Power Grid for Electric Vehicles - A Case Study on a Swedish Low Voltage Grid

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# Hosting Capacity of the Power Grid for Electric Vehicles - A Case Study on a Swedish Low Voltage Grid

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**Abstract.** Hosting capacity (HC) is described as the maximum amount of new production or consumption that can be added to the grid without causing a violation. In this case study, a deterministic approach is used to investigate the HC of electric vehicle (EV) charging in a low-voltage grid, containing 13 detached single-family houses. It investigates how different parameters affect the HC, and what is causing the violation in the grid. Two different performance indices (PI) are used in the study: power cable overloading and voltage drop. The local grid is simulated for one year for four cases and the HC is derived for these. The cases are distinguished by two different violation thresholds for the voltage drop and two different implementation orders of the location of the charging. The results show that the HC of the grid is 6-11 EVs charging simultaneously. The difference in HC is primarily due to variation in the baseload through the year and location of charging. The cable between the substation and the first cable cabinet was the major contributor to the fault, and the PI causing the violation differed depending on what case was used.

## 1. Introduction

The implementation of electric vehicles (EVs) is promoted as an important measure to fight climate change [1], but it comes with challenges. One example is the potential negative impacts on the electric power grid when the EVs are charging, described by Nour et. al. [2]. This paper will focus on two of the negative impacts, voltage drop and overloading of power cables, from here on named the performance indices (PIs). When the limit of a PI is reached, the so-called hosting capacity (HC) is obtained. The HC is described as “the maximum amount of generation that can be integrated into the power system, while still maintaining its performance within acceptable limits” [3]. The concept of HC can also be used in terms of new consumption instead of generation, as it will be in this study. Previous examples of this are HC case studies on the Swedish distribution grid for combined EV and photovoltaics (PV) [4] and EV or PV [5]. Another is HC analysis of slow and fast charging EVs [6]. When dealing with HC analysis of EV charging there are several uncertainties to handle. For example, the location of the EVs, the power the EVs are charged with, charging duration, and at what time it will charge. Furthermore, to estimate the HC in a grid, several assessment methods can be used, described by Abideen et. al [7]. In this paper, a deterministic assessment method is used to handle the uncertainties.

In HC analysis, one has to decide which limit to use for the PI. The limit for voltage variations is specified in the voltage characteristic standard EN 50160 which defines that under normal operation,



the voltage variation should not exceed +/- 10% of the nominal voltage [8]. However, according to the distribution system operator (DSO) in this study, Borlänge Energi Elnät, it is desirable to keep the variation within +/- 5% to avoid disturbances for the customers.

This paper aims to study the HC of EV charging in a low voltage (LV) grid by investigating how it changes based on different circumstances and to understand the causes of the violation. In this study HC is defined as the maximum number of EVs that can be charged together with the base load, without exceeding the specific PI limit. The method used in the study does not include driving patterns or realistic times for charging the EVs, instead, the purpose is to give the DSO a quantification of the abilities the grid has to host the charging. One can then interpret the result and consider how likely it is for this to happen and get an idea of how urgent it is to take action to increase the HC or put other measures to control the charging. To reach the aim the following research question and sub-questions are to be answered:

*How many EVs can charge simultaneously in a LV grid until the HC is reached?*

*- How does the HC change through the year?*

*- How does the HC change based on locations of the charging and different limits for the PI?*

*- Which PI is the limiting one?*

*- Which part of the grid is the major contributor to the violation?*

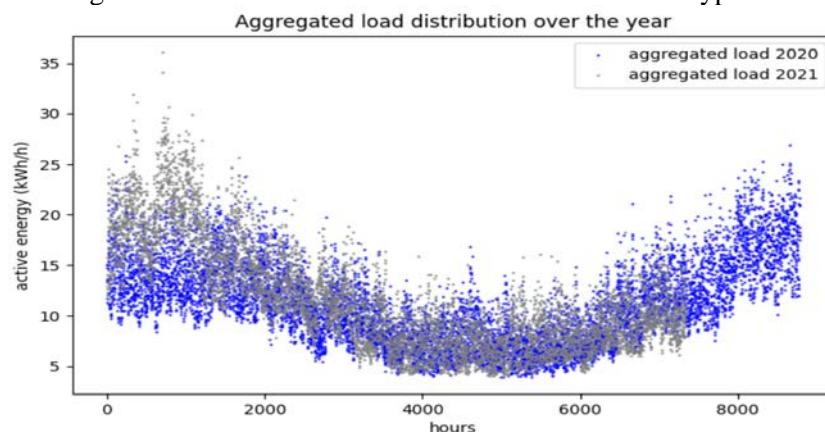
## 2. Methodology

### 2.1. Power grid data

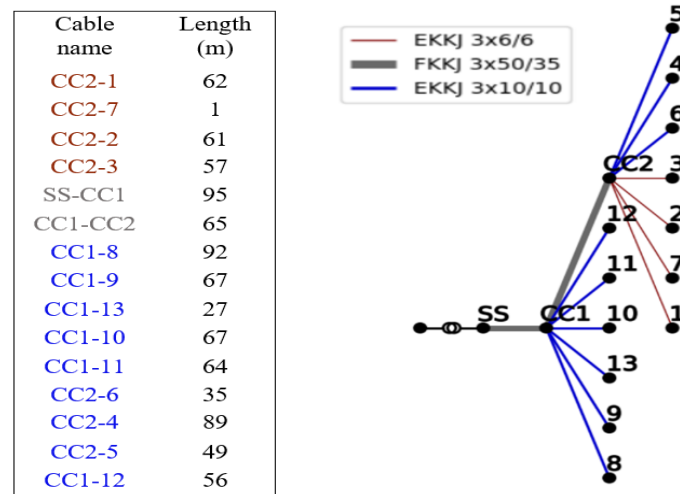
The studied grid is a part of Borlänge Energi power grid, which is a power distribution grid located in the central part of Sweden, feeding approximately 30,000 customer connection points with electricity. Due to the scope of this study and the availability of historical load data, only a fraction of the grid was analyzed. The studied part contains distribution cables feeding 13 customers in 3-phase connections and a 10.5/0.4 kV transformer without an on-load tap changer. The area consists of detached single-family houses with district heating availability.

The available historical load data contained more than two years of measured hourly averaged active energy consumption (kWh/h) for 13 households in the LV grid. However, only data for one full calendar year (the year 2020) was available and used in the HC analysis. A perfectly balanced load over the three phases was assumed. No reactive energy consumption for the whole period was obtained, thus a simplification was made by setting assuming it was zero. In figure 1 the aggregated historical load for the 13 customers for the year 2020 and part of 2021 is shown. The beginning of the year 2020 was relatively warm, which is the likely cause of the lower consumption compared to the beginning of 2021.

Information about to and from which bus the cable is connected and the length of the cable were extracted from the network information system used by Borlänge Energi. This data together with the grid structure including the substation (SS), cable cabinets (CC) and numbered customer connection points can be seen in figure 2. The cables are colored based on their cable type.



**Figure 1.** Aggregated historical load for the year 2020 (blue) and part of 2021 (grey).



**Figure 2.** Structure of the investigated grid with information of cable types and lengths.

The cable types and their characteristic data used in the simulation model can be seen in table 1.

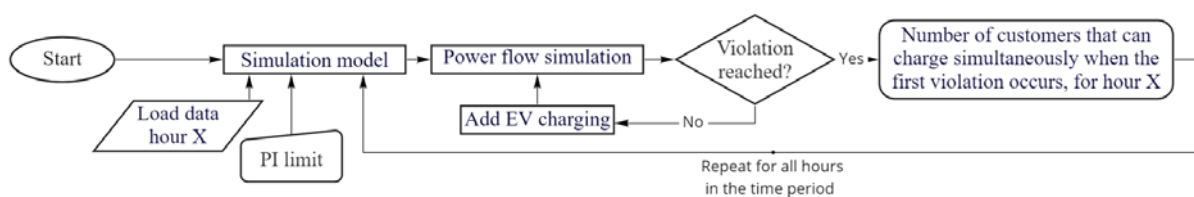
**Table 1.** The different cable types in the investigated grid.

Cable type	Resistance (ohm/km)	Inductance (ohm/km)	Rated current (ampere)
EKKJ 3x6/6	3.08	0.093	57
FKKJ 3x50/35	0.39	0.078	190
EKKJ 3x10/10	1.83	0.087	77

In the simulations, the voltage level of the high-voltage side of the transformer was fixed, but in reality, this voltage level differs for different load situations in the grid. This affect is thus not accounted for in this study. The voltage level was based on a high-load situation and obtained from the network information system along with performance data of the transformer. The rated voltage of the high- and low-voltage side of the transformer is 10.5 kV and 0.4 kV respectively. However, the transformers were set to run on a higher voltage, 10.6 kV, to keep the voltage higher at the customers and so allow a higher load.

## 2.2. Method for the simulation

In this study, the power system analysis tool pandapower has been used to build a simulation model. Pandapower is based on Python programming language and includes a Newton-Raphson power flow solver [9]. Data for the grid components were imported to the simulation model to represent the grid. The historical load data were assigned to their corresponding connection point and used as base loads in the simulations. HC simulations for EV charging were then performed according to the flow chart in figure 3.



**Figure 3.** Flow chart of the HC simulation.

In the simulation, historical load data for a certain hour were used and a power flow simulation was performed. If no PI were violated, EV charging was assigned to one customer based on a priority list. This process was iterated until the first violation of a PI occurred. The number of vehicles charging was then collected. The whole process was repeated for all hours of the year.

For the PI of cable loading, the calculated value of the current through a cable was compared to the cable's rated current, which results in a percentage of the loading in the cable. The limit of the loading PI was set to 100%. Two different limits for the PI of voltage drop were investigated: 5% voltage drop (which is desirable to keep within according to the DSO) and 10% voltage drop (limit according to EN 50160). The voltage drop is relative to the nominal phase-to-phase voltage of 400 volts.

The EV charging was simulated as a constant power load, consuming only active power and symmetrically distributed over the three phases. To determine the location where the EV charging will occur, a deterministic approach was used in the simulations. A priority list was made to decide at which customer a charging load will be added first, where it will be added secondly, and so on. The order of the priority list started from the customer who got the highest voltage drop to the customer who got the lowest voltage drop, based on a load configuration with an equal amount of load for every customer. Figure 2 shows the structure of the grid, where the numbering of the customer connection points corresponds to the order in the priority list.

The charging power used in the simulation was set to 11 kW as long as the total load was smaller or equal to 17.25 kW. If the total load would exceed 17.25 kW, the EV load was decreased to correspond to a total load of 17.25 kW. 17.25 kW corresponds to a load of 25 ampere, which is higher than the majority of the connection point fuses of the investigated customers. However, the customer can upgrade their fuse up to 25 amperes without a need to upgrade the connection cable. Instead of deciding what hour the EV will charge the charging of 11 kW was put on all hours of the year.

To investigate how the location of the charging affects the HC, the priority list was applied both forward and backward. The forward application starts with the customers getting the highest voltage drop and is therefore named "worst case". The backward application of the list, starting with the customers getting the lowest voltage drop, is named "best case". Two different voltage levels were investigated as mentioned earlier, which lead to four different test cases for the HC analysis:

- Case 1, best case and 5% voltage drop
- Case 2, worst case and 5% voltage drop
- Case 3, best case and 10% voltage drop
- Case 4, worst case and 10% voltage drop

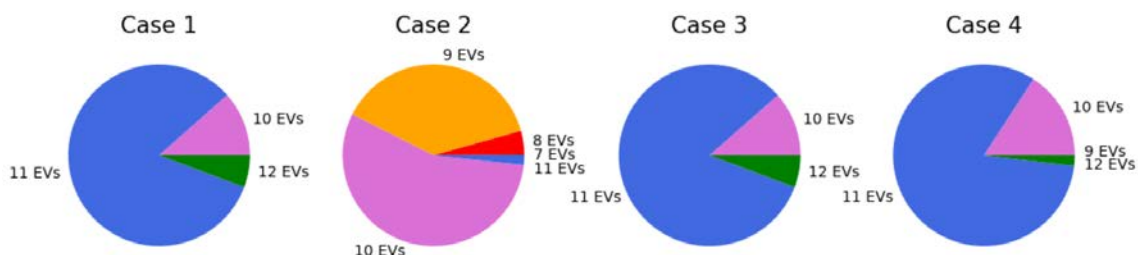
All cases used 100% cable loading as the limit for the second PI.

### 3. Results

The results chapter answers the main research question "How many EVs can charge simultaneously in a LV grid until the HC is reached?" and is divided by the sub-questions.

*How does the HC change throughout the year? How does the HC change based on locations of the charging and different limits for the PI?*

Figure 4 shows fraction of the year having a violation with the given number of EVs charging simultaneously. The chart includes results from all hours of 2020 for the four different cases.

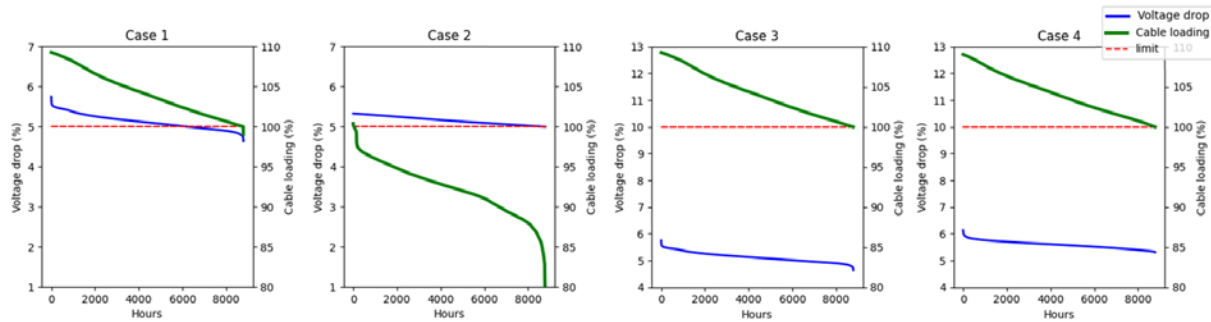


**Figure 4.** Fraction of the year having a violation with the given number of EVs.

For example, in Case 1, approximately 80% of the hours in the year, 11 customers were charging simultaneously when the first violation occurred. In this case, the yearly difference in HC is two vehicles. The differences in the results for best case and worst case corresponds to differences in location of charging. The differences between Cases 1 and 3, and between Cases 2 and 4 corresponds to the differences in performance limit for the voltage drop. Cases 1, 3 and 4 have similar results whereas Case 2 can host fewer EVs charging at the same time.

*Which PI is the limiting one?*

Figure 5. Duration curves of the PIs when a violation occurs. The red dashed line is the PI limit for the case. The cable loading has been the limiting PI for most cases.



**Figure 5.** Duration curves of the PIs when a violation occurs. The red dashed line is the PI limit for the case.

Case 2 stands out from the other cases because the voltage drop is the limiting factor almost all the time. In Case 1, the voltage drop and loading are both violated for the majority of the hours. Cases 3 and 4 give the same result even though the order of the priority list is opposite, with both having violations with cable loading while the voltage drop is not close to its limit of 10%.

*Which part of the grid is the major contributor to the violation?*

Cable SS-CC1 is the problematic one when it comes to overloading. It is the first cable to get overloaded in all cases where the overloading was the limiting PI (Cases 1, 3 and 4). For the cases with voltage drop as the limiting PI (Cases 1 and 2), the customers that get too low voltage are customers 2-4. However, in terms of under-voltage, the problem can be somewhere between the substation and the customer. Therefore, a comparison of the voltage drops was made. If every customer has a total load of 11 kW, the corresponding voltage drops are as shown in table 2, which also shows the percentage of the total voltage drop the components contribute to. Only the customer cable that gave the highest voltage drop is represented in the table.

**Table 2.** Voltage drop and contribution of total voltage drop caused by different power cables in the grid, based on a load of 11 kW per customer.

Cable	SS-CC1	CC1-CC2	CC-customer, max
Voltage drop (%)	3.4	1.3	1.4
Percent of total voltage drop (%)	56	21	23

As can be seen in table 2, cable SS-CC1 corresponds to the highest voltage drop.

#### 4. Discussion

The method used in this study can be used by DSOs to get an estimate of how many EVs that can charge simultaneously in the grid and serve as a basis to decide whether measures are needed to increase the HC. In the analysis, charging behavior is not included, instead, the load is added for all the hours of the year. This does not give a realistic case, but generates a result that shows the

differences in HC through the year. In reality, more EVs can be used in the area as long as the charging is spread out in time. But, if for example the charging would be based on price signals, the possibility of many vehicles charging simultaneously is high.

Bollen et. al. [5] described that the HC is not a unique value, instead, it depends on several factors such as the simulation model and data used for the HC calculation, what PI is evaluated, and the limit of the PI. In this paper, the variety in HC has been tested for yearly variation in baseload data, different limits of PI, and change in the simulation model (in terms of location of the charging). The variation in baseload gave the largest differences in HC for all cases. For the cases with a PI limit of 5% voltage drop (Cases 1 and 2), the location of charging were also impacting the HC.

The overloading of cable SS-CC1 was the limiting factor in three of four cases. The same cable was also the major contributor to the voltage drop. Upgrading the cable would probably lead to a higher HC of the grid. However, reinforcement of the grid is not the only measure to enhance the HC. Other solutions are for example demand response, energy storage, on-load tap changing transformers, and reactive power control [10].

The number of vehicles possible to charge simultaneously throughout the year does not vary much for the cases where the cable loading was the limiting factor. This can be explained by the baseload being small compared to the added EV load. The variation is two vehicles for the majority of the time (22 kW), which approximately corresponds to the yearly variation in aggregated baseload for the year 2020, as was seen in figure 1.

The results in this paper are tied to a specific grid and cannot be directly transferred to other grids, but the method should be applicable when used with the network and consumer data for the particular grid to be evaluated.

## 5. Conclusions

In this paper, a deterministic HC assessment method is applied. The method is based on different limits for the PI, different implementation orders of EVs, and performed for all hours of the year. In the cases with higher tolerance of voltage drop, Cases 3 and 4, there is only a slight difference in the HC. The cable loading was the limiting factor for all hours in both cases. The small difference is probably due to that lower voltages in the worst case (Case 4) in combination with constant power loads which leads to higher currents and so higher loading of the cables. However, when the voltage drop is the limiting factor, the differences in location of the charging has a larger effect, as can be seen when comparing Cases 1 and 2. This is due to that the voltage drop gets higher the further out in the grid the load is applied.

In this specific grid, 7-12 customers need to charge EVs simultaneously for the first violation to occur. The HC is the maximum amount before a violation, i.e. 6-11 customers. If one assumes that the households have one EV each, it means that 46% to 85% of them can charge with 11 kW at the same time. The difference depended on variation in the baseload, what voltage limit was used, and the location of the charging. Location of charging for a limit of 5% voltage drop and variation in base-load gave the largest differences in HC. The PI causing the violation were case dependent and the major contributor to the fault was the cable between the substation and the first cable cabinet.

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