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Evaluation and variability of power grid hosting capacity for electric vehicles

Case studies of residential areas in Sweden

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Abstract

Electric vehicles (EVs) are increasing in popularity and play an important role in decarbonizing the transport sector. However, a growing EV fleet can cause problems for power grids as the grids are not initially designed for EV charging. The potential of a power grid to accommodate EV loads can be assessed through hosting capacity (HC) analysis. The HC is grid specific and varies, therefore it is necessary to conduct analysis that reflects local conditions and covers uncertainties and correlations over time.

This theses aims to investigate the HC for EVs in existing residential power grids, and to gain a better understanding of how it varies based on how the EVs are implemented and charged. The work is in collaboration with a distribution system operator (DSO) and is based on two case studies using real-life data reflecting conditions in Swedish grids. Combinations of different HC assessment methods have been used and the HC is evaluated based on cable loading, transformer loading and voltage deviation. Additionally, the study investigated three distinct charging strategies: charging on arrival, evenly spread charging over whole connection period, and charging at the lowest spot price.

The results show that decisions on acceptable voltage deviation limit can have a large influence on the HC as does the charging strategy used. A charging strategy based on energy prices resulted in the lowest HC, as numerous EVs charging simultaneously caused high power peaks during low spot price periods. Charging on arrival was the second worst strategy, as the peak power coincided with household demand. The best strategy was to evenly spread out the charging, resulting in fewer violations for 100% EV implementation compared to the other two strategies for 25% EV implementation.

The findings underscore the necessity for coordinated charging controls for EV fleets or diversified power tariffs to balance power on a large scale in order to use the grids efficiently.

Keywords: Hosting capacity (HC), Power grid, Electric vehicle (EV), Charging strategies, Power flow simulations, Uncertainty analysis

Sammanfattning

Elfordon ökar i popularitet och spelar en viktig roll i att minska koldioxidutsläppen från transportsektorn. En växande elfordonsflotta kan dock orsaka problem för elnäten eftersom elnäten från början inte är dimensionerade för elbilsladdning. Ett elnäts potential för elbilsladdning kan bedömas genom en analys av värdkapaciteten (eng. hosting capacity (HC)). HC är elnätsspecifikt och varierar, därför är det nödvändigt att genomföra analyser som speglar lokala förhållanden och inkluderar osäkerheter och korrelationer över tid.

Syftet med denna avhandling är att undersöka HC för elbilar i befintliga elnät i bostadsområden, och att få en bättre förståelse för hur kapaciteten varierar beroende på hur elbilarna implementeras och laddas. Arbetet utförs i samarbete med en lokalnätsägare och baseras på två fallstudier med fältdata som återspeglar förhållanden i svenska elnät. Kombinationer av olika HC-bedömningsmetoder har använts och HC har utvärderats baserat på kabelbelastning, transformatorbelastning och spänningsavvikelse. Tre olika laddningsstrategier undersöktes: laddning vid ankomst, jämnt fördelad laddning när bilen är inkopplad och laddning vid lägsta spotpris.

Resultaten visar att gränsvärdet för spänningsavvikelsen kan ha en stor påverkan på HC samt vilken laddstrategi som används. En laddstrategi baserad på energipriser resulterade i lägst HC, detta eftersom många elbilar laddade samtidigt och orsakade höga effekttoppar under perioder med låga spotpriser. Laddning vid ankomst var den näst sämsta strategin, detta eftersom effekttopparna sammanföll med hushållens effekttoppar. Den bästa strategin var att sprida ut laddningen. Detta resulterade i färre överträdelser för 100% elbilsimplementering jämfört med de andra två strategierna för 25% elbilsimplementering.

Resultaten understryker behovet av samordnade kontrollsystem för laddning av elbilsflottor eller diversifierade effekttariffer. Detta för att kapa effekttoppar i stor skala och kunna använda elnäten effektivare.

Nyckelord: Värdkapacitet (HC), elnät, elfordon (EV), laddningsstrategier, kraftflödessimuleringar, osäkerhetsanalys

List of Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals.

Paper I

Sandström, M., Bales, C., & Dotzauer, E. (2022). Hosting Capacity of the Power Grid for Electric Vehicles – A Case Study on a Swedish Low Voltage Grid. *IOP Conference Series: Earth and Environmental Science* vol 1050 (nr 1), 7th International Conference on Sustainable and Renewable Energy Engineering (ICSREE 2022) 05/05/2022 - 07/05/2022 Online, doi: 10.1088/1755-1315/1050/1/012008

Paper II

Sandström, M., Huang, P., Bales, C., & Dotzauer, E. (2023). Evaluation of hosting capacity of the power grid for electric vehicles – A case study in a Swedish residential area. *Energy* vol 284(nr) doi: https://doi.org/10.1016/j.energy.2023.129293

My contributions:

- Paper I – Formulating the research questions, deciding on the method and case studies, collecting the data, building the data model and algorithms, conducting the simulations, and writing the paper, with support from the co-authors.

- Paper II – Formulating the research questions, deciding on the method and case studies, collecting the data, building the data model and algorithms, conducting the simulations, and writing most of the paper, with support from the co-authors.

Abbreviations

AC	Alternating current
BEV	Battery electric vehicle
DC	Direct current
DSO	Distribution system operator
EV	Electric vehicle
HC	Hosting capacity
HV	High voltage
LV	Low voltage
MC	Monte Carlo
MV	Medium voltage
NIS	Network information system
PHEV	Plug-in hybrid electric vehicle
PI	Performance index
PV	Photovoltaics
rms	root mean square
TSO	Transmission system operator
V2G	Vehicle-to-grid

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1. Introduction

Addressing climate change, driven by greenhouse gas emissions, is an urgent matter. Currently, almost 80% of the global energy supply is based on fossil fuels [1]. There is an emerging need to transition the energy sector to more sustainable options. Significant increases in renewable energy capacity and electrification are considered crucial measures to reduce emissions [1].

The transport sector heavily relies on fossil fuels and is accountable for almost a quarter of global energy-related CO_2 emissions. Road transport is responsible for over three-quarters of the sector's CO_2 emissions and contributes to around 45% of the global oil demand [1, 2]. Accelerating the deployment of electric vehicles (EVs) in road transport, together with decarbonization of the power supply, are considered the main levers to decarbonize the transport sector [2]. Both of these aspects are essential because the emissions resulting from driving an EV heavily depend on the sources of the electricity production used to charge it [3].

EVs are becoming increasingly popular worldwide. In 2022, they accounted for 14% of all new car sales, a notable increase from the previous two years of 9% and less than 5%, respectively [4]. In Sweden, EVs have already captured a significant portion of the market share. In 2022 half of all newly registered passenger cars were EVs, and they currently make up 11% of the national passenger car fleet [5, 6].

Most EV charging takes place in the local distribution grid, and most of the time at residential chargers [7]. As many power grids have not traditionally been designed to host a large proportion of this type of load, a growing fleet of EVs can pose severe challenges to the grids. These challenges include voltage deviation, overloading of power system equipment, harmonics injection, increased peak demand and power losses, and phase unbalance [8, 9]. This may result in malfunction, shortened lifetime and damage to equipment [10]. It is therefore important that the grid remains within certain performance limits to ensure the quality of the electricity and the security of supply. Analysis of the power grid's capacity to host new types of loads while staying within performance limits is therefore essential for future planning and investment decisions in the grid.

1.1. Aim and objective

The capacity of a power grid to perform as desired is influenced by its design and the type of equipment connected to it. Where, when and how the units are used also affects the grid capacity. A commonly used term in this context is the hosting capacity (HC). It refers to the amount of new generation or new load added to the power grid at which the performance of the grid becomes unacceptable [10]. The HC is evaluated based on different performance indices (PI). When the limit of a PI is reached, the HC is obtained.

This thesis evaluates the HC of existing residential power grids and examines how it varies based on how new load units, in the form of EVs, are implemented and charged. The aim is to provide DSOs with insights into how a transition in the car fleet may affect their power grids and to demonstrate the potential for using the grids in a resource efficient manner.

The research questions addressed in this thesis are:

- To what extent is a residential grid's HC for EVs reached for different charging strategies and different EV implementation levels?
- Which PI primarily limits the HC for EVs in a residential grid: cable loading, transformer loading or voltage deviation?
- How does the location of the EV charging affect the HC in a residential grid, and how does changing the voltage deviation tolerance affect the result?

To address this, case studies of existing power grids are conducted and several simulations are carried out.

1.2. Scope and limitations

This thesis is based on case studies from two different residential areas in Borlänge and therefore covers a very limited geographical area in Sweden. Consequently, the results are specific to the studied cases. However, it is expected that the conclusions drawn from this thesis are applicable to other parts of Sweden, as the grids in the case study areas have a typical structure used for Swedish local distribution networks. Furthermore, it is expected that the trends observed in the variation of HC by changing different factors can also be applied outside of Sweden.

When simulating the EV charging load, some simplifications were made. The charging was simulated as three-phase loads with a power factor of 1 and a maximum charging power of 11 kW. Furthermore, the analysis is based on empirical data and therefore assumes that behavioral patterns are the same as those in the data set.

The HC analysis is based on thresholds for slow voltage changes and component overloads. However, there are also other parameters affecting the power quality that were not included in the analysis due to data limitations. The available data on electricity consumption in the area was for the total three-phase hourly averaged energy. Therefore, other aspects of power quality that require different data measurements or higher time resolution are not included, such as fast or short-term voltage variations, voltage asymmetries and harmonics. Furthermore, the requirements for slow voltage changes are based on measurements of 10-minute averages [11]. However, only hourly averages were available for the historical load data used in the HC analysis in this thesis.

2. Background

2.1. The electric power system

The power system is a complex interconnected network that can be divided into four main parts: generation, transmission, distribution and loads [12]. In the following two sub-chapters the physical design and the market of the Swedish electric power system are described.

2.1.1. The electric power grid in Sweden

In Sweden, the national electricity transmission grid consists of approximately 17,500 km of power lines and is state-owned by the transmission system operator (TSO), Svenska kraftnät [13, 14]. Large electricity generating plants and some very large consumers are usually connected directly to the national power grid. The distribution grids in Sweden consist of both regional power grids and local power grids and are owned by the distribution system operators (DSOs) [14, 15]. The regional power grid distributes electricity from the national power grid to the local power grids or directly to large electricity consumers. The local power grids supply electricity to the majority of the consumers, such as households or businesses. Medium-scale producers are typically connected to the regional power grid, while small-scale producers are typically connected to the local power grid [15]. The connection point between a consumer and the power grid can be supplied in a single-phase or three-phase configuration. In Sweden, a three-phase power supply is the established standard for residential consumers [16]. The general structure of Sweden's power grid is illustrated in Figure 1. This thesis has a focus on the local power grid, shown in the leftmost part of the figure.

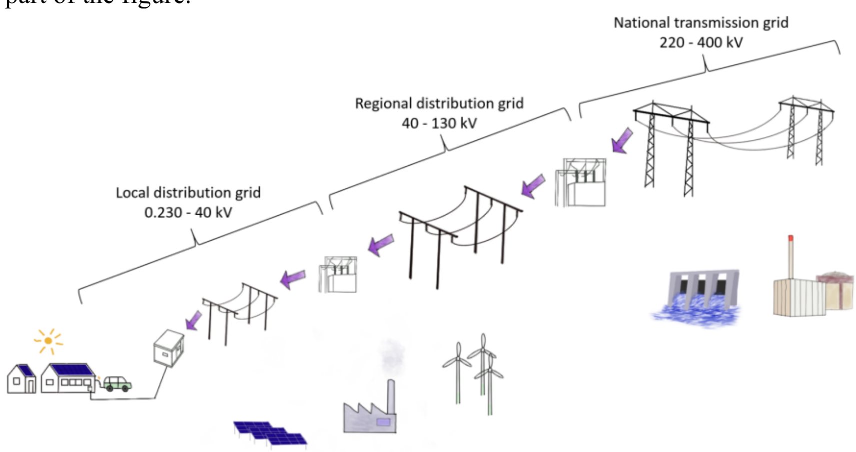


Figure 1. The general structure of the Swedish electric power grid.

2.1.2. The electricity market in Sweden

The consumer price of electricity consists of three main parts: 1. the cost of the electricity consumed paid to the electricity trading company, 2. the power grid charges paid to the DSO for transporting the electricity to the consumer and 3. taxes and fees [17]. The first two parts and their relation to capacity limitations in the power grid will be explained below.

The Nordic countries have a liberalized electricity market where participants of the electricity market can buy and sell electricity on power exchange platforms, such as Nord Pool [18]. At Nord Pool, market prices are set to balance supply and demand, which is important because the grid cannot store electricity. The platform has an auction-based day-ahead market where it collects bids and offers from producers and consumers and calculates the hourly electricity price. The hourly electricity price for the following day is then published [19]. This hourly electricity price is referred to in this thesis as the spot price and is linked to the cost of the electricity consumed. In Sweden, the electricity market is divided into four bidding areas. Spot price differences between the areas arise when transmission capacity between the areas is limited, meaning there are physical limitations in the national grid [18]. However, capacity limitations can occur in all parts of the power grid, i.e. in the transmission, regional or local power grids, as will be described below.

The TSO has contracts with its customers, e.g. regional DSOs, which regulate the amount of transmission capacity the customer subscribes to. If the customer requires more electricity than is included in the subscription, a temporary power subscription can be requested and will be granted if there is available capacity in the national transmission power grid. Except for the temporary power subscriptions, it is not allowed to exceed the power subscription, but if it is done, a penalty fee has to be paid [20]. In a similar way, regional DSOs have capacity subscriptions to their customers, e.g. local DSOs. If no more electricity can be transferred, either because of physical limitations in the power grids or because it is not possible to extend the subscription from the supplying power grid, a situation of capacity shortage occurs. In these situations, the power grids need to be reinforced or flexibility needs to be bought. There are existing pilot projects for local flexibility markets, where stakeholders can trade flexible resources to free up capacity in the power grids [21].

The majority of the power grid customers are connected to the local power grids. The most common way for household customers to pay for their power grid charges is through fuse-based tariffs. However, the introduction of power tariffs has become more popular in recent years [22]. A power tariff is a grid tariff where at least one of the variable charges is a charge based on the power used by the consumer (i.e. the amount of electricity consumed hour by hour) [23]. By the year 2027, DSOs are obligated to charge all consumers based on time differentiated power tariffs to encourage efficient grid use [23, 24].

2.2. Residential electricity use

In Sweden, there are approximately 5 million households. Half of these are apartments in multifamily buildings, while around 40% are detached one- and two-dwelling houses and terraced houses. The remaining 10 percent belong to buildings that are not primarily intended for housing, special housing, or where housing information is missing [25].

The energy use in a dwelling can be divided into household electricity, energy used for heating and hot water and, in the case of multi-family buildings, property electricity (e.g. to run elevators and central building systems).

The household electricity use depends on the appliances in the household, their electricity demand and the use of the appliances [26]. The average annual household electricity consumption for a one- or two-dwelling house in Sweden is about 5,800 kWh per household, and the heating energy consumption for space heating and hot water is about 16,000 kWh. However, different energy sources/carriers can be used for heating, with electricity being the most common source, followed by biofuels and district heating [27]. Therefore, the total electricity consumption in a dwelling is strongly dependent on the heating system used. Furthermore, electrical heating can be divided into different categories, direct electrical heating and heat pumps. In 2021, almost 70% of the one- or two-dwelling houses in Sweden were equipped with heat pumps [28].

The electricity load pattern over a day also differs for different households, but attempts have been made to produce load profiles for different household categories, weekdays and seasons. One example is given in Ref. [26], where a tool for stochastic generation of synthetic household electricity load profiles has been developed based on activity patterns. Another example is shown in Figure 2 which shows general load profiles for different household types. The profiles are based on weekdays and outdoor temperatures between 0 and -10 °C and show the average load profile of a household. The profiles are predefined in the network information system (NIS) used by the DSO in this study [29] and are based on a report by Svenska Elverksföreningen [30].

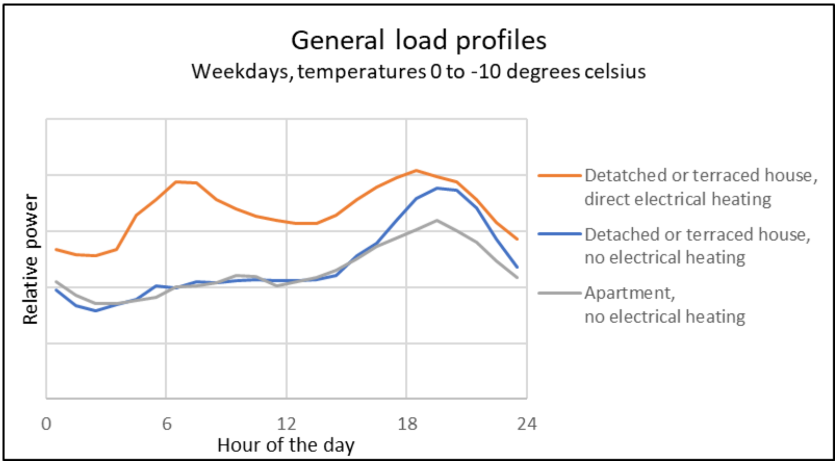


Figure 2. General load profiles for a winter weekday for different household categories. Profiles derived from [29, 30]. Note that the y-axis shows the relative power, which should be scaled based on a customer's annual average power.

Svenska Elverksföreningen published the general load profiles in 1991. They state that the profiles are still relevant, but that it is necessary to take into account the changes that have taken place among customers who have installed heat pumps [31]. The introduction of other new appliances may also change the appearance of such general load profiles. EVs are identified as a major driver of changes to existing load profiles, and their management, such as different charging strategies, will play a central role [32].

In this thesis, the household load refers to the total electricity load in a residential household, including the electrical load for heating, if any, and excluding new EV charging load or new solar photovoltaics (PV) production.

2.3. Electric vehicles

In this thesis, EV refers to vehicles that can be charged from the electric power grid, namely, battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). A BEV is powered solely by an electric battery, while a PHEV uses both an electric battery and an internal combustion engine [7].

In Sweden, BEVs and PHEVs make up roughly equal proportions of the EV passenger car fleet, and lately it has become more popular to buy a BEV than a PHEV [6, 33].

2.3.1. EV charging

The electric power grid supplies alternating current (AC), but the battery of EVs receives direct current (DC). A conversion from AC to DC is therefore required before the power reaches the battery. Where this conversion takes place is the difference between the so-called AC and DC charging. With DC charging, the conversion takes place outside the EV, allowing larger converters to be used because there is less concern about space limitations. This allows for higher charging power, resulting in shorter charging times. DC charging, or “fast charging”, is common at public charging stations and can provide power between 50 to 800 kW [34]. AC charging on the other hand, is common when the EV is charged at home. Here the conversion from AC to DC takes place inside the EV in the onboard charger [34]. A schematic illustration of the difference between using a DC and an AC charger is shown in Figure 3.

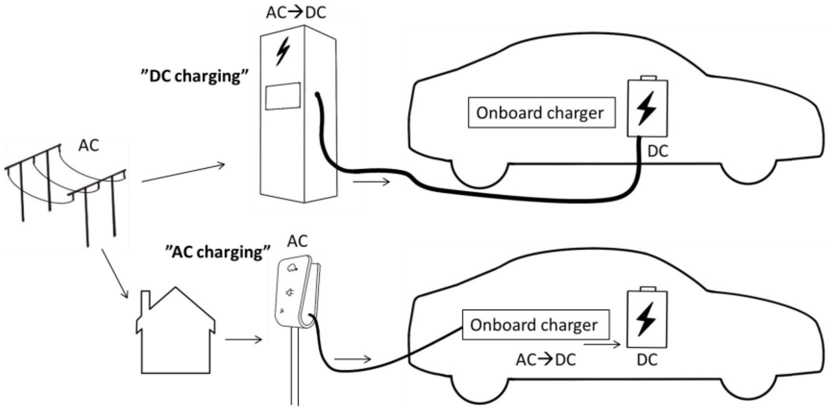


Figure 3. Schematic illustration of the difference between using a DC and an AC charger.

The power available for home charging is therefore limited by the capacity of the onboard charger. Some onboard chargers can accept 3-phase charging, while others can only accept 1-phase and sometimes 2-phase charging. The majority of the BEVs registered in Sweden in 2021 had an onboard charger of 11 kW (3-phase) and a PHEV of 3.7 kW (1-phase) [6, 35]. The capacity of home charging is also dependent on the size of the cable to the house, the main fuse, if an external charger is used and the capacity of the external charger.

The additional load of charging an EV at home can be relatively high compared to the household load. As a reference, Figure 4 shows a duration curve containing all the hourly load values of individual households from the case study presented in Paper II. The data covers a two-week winter period and the households are located in a district heating area.

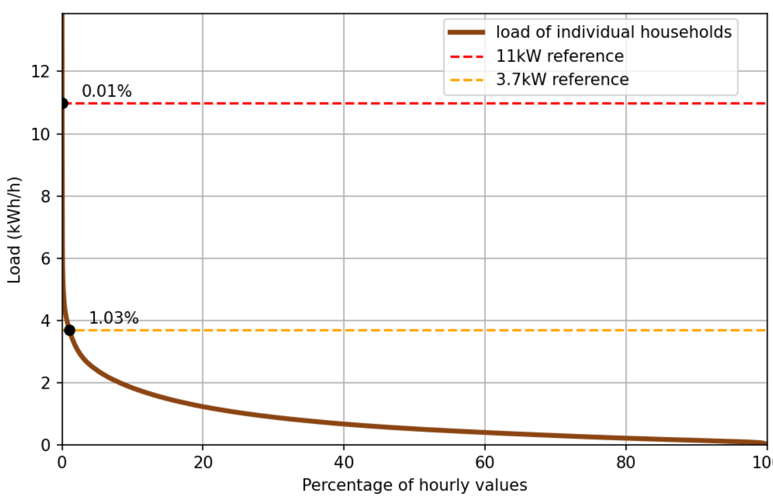


Figure 4. Duration curve of all hourly load values for all individual households in the case study presented in Paper II. As a reference, only 0.01% and 1.03% of all hourly load values exceeded 11 kW and 3.7 kW respectively.

The figure shows that very few hourly values for individual households exceed the potential power of home charging an EV. Most of the time the household power is much lower. It is however important to note that the data is derived from an area with district heating. If heating is covered by electricity the household load would be higher.

When an EV is plugged in, several charging strategies can be used. If the EV is charged immediately on arrival at the home, the peak load from the EV is likely to coincide with the existing evening peak load from the households [36]. However, on average cars are parked for at least 92% of the time [37]. This opens up the potential to shift the EV charging load through smart charging controls, while still ensuring a fully charged EV upon departure. Several benefits can be achieved through the use of smart charging. These include reducing peak loads, grid losses and charging costs, avoiding grid overloading and voltage problems, increasing PV utilization, providing frequency regulation services and balancing three-phase loads [38]. However, some charging strategies can cause problems for the power grid. The so-called avalanche effect can occur, i.e. a large number of EVs change their charging power rate in response to low electricity price signals, leading to a minimization of system performance [7, 39].

There are already some commercially available automated smart charging strategies on the market in Sweden today. For example, solutions that charge EVs at times of low electricity prices and/or optimize PV self-utilization [40-43]. Communication for the charging control can be via the connected EVs API (Application Program Interface) or the charging station [44].

2.3.2. *EV behavior and charging modeling*

Charging behavior is key to understanding the impact of EVs, and EV charging models can be used to simulate the impact on the power grid.

Some existing studies have examined charging behavior based on empirical EV data. For example, a study based on EV charging data from the US and Canada found that PHEVs are charged on average once every 24 hours, and most often at night [45]. Similar results were found in a UK-based study, where 70% charged once a day and the rest more frequently, and the peak EV load was expected to coincide with the existing evening peak load [36].

EV charging behavior can be simulated to produce synthetic charging load profiles, which in turn can be used in power flow simulations to investigate the impact on the grid. The profiles can be generated by the use of different methods. One can for example base it on surveys and statistical data on transportation behavior [46], or from combinations of these with real-world EV charging data [47, 48].

2.4. Hosting Capacity of the power grid

Many different PIs can be used in HC analysis and the resulting HC depends on which PI is considered and what limit is set for it. The level of risk the DSO is prepared to take affects the HC: the higher the risk, the higher the HC [49, 50].

Negative impacts on the power grid are for example overloading of power system equipment, voltage deviations, increased peak demand and power losses, harmonic injections and phase unbalances [8, 9]. Improving the HC in a power grid involves measures such as reinforcing or reconfiguring the grid, energy storage or demand response, reactive power control and the use of on-load tap changing transformers [51]. However, there is a trade-off between the risk of poor voltage quality and costly over-dimensioning of the grid [49].

In this thesis, HC refers to the amount of EV charging that is added before violations occur in the grid, and the PIs investigated are voltage deviations and overloading of cables and transformers.

2.4.1. Quality of the transmitted electricity

To maintain acceptable grid performance, electricity must have a certain quality. The concept of power quality revolves around the electrical interaction between the power grid and its customers. It consists of two parts, current quality and voltage quality. Current quality is how equipment current impacts the power system, and voltage quality is how the power system voltage affects the equipment connected to it [52].

The Swedish Electricity Act states that the transmission of electricity supplied by a TSO/DSO must be of good quality. Furthermore, the government can issue regulations to fulfill the requirement of good quality [53]. The EIFS 2023:3 is such a regulation and can be divided into two parts, one regulating power outages and the other concerning voltage quality [11]. There are several measures of how to keep a good voltage quality, this thesis focuses on the slow voltage variations.

2.5. Previous research

2.5.1. HC assessment methods

There are several uncertainties in estimating the grid HC for EVs. These include the duration and time-point of charging, the location of where the EV is charged and the power at which the EV is charged. Furthermore, several assessment methods can be used to analyze the HC for EVs, such as the deterministic method, the stochastic method, and the time series method [54].

The deterministic approach can be useful for worst-case and mean-case scenarios but does not account for uncertainty. The stochastic and time series models, on the other hand, can account for the uncertainties associated with EV charging and its impact on the grid [55]. The time series approach takes into account the dynamic nature of load and generation in the load profiles used for load flow calculations performed at each time step in the dataset [56].

Time series approaches to estimating HC have previously been applied by using a profile generator to generate synthetic EV load profiles (e.g., [46, 57]) and by including the effects of different charging strategies (e.g., [46, 58]). The time series method involves the correlation of different loads over time but does not take into account the uncertainties in the location of the EV integration into the grid.

The stochastic approach involves the estimation of multiple scenarios to account for uncertainties [51]. Several methods can be applied to generate the random scenarios. Monte Carlo (MC) simulation is commonly used. Numerous load flow calculations are then conducted to create a wide range of results [56]. The stochastic approach with MC simulations has been carried out in [49, 50, 59]. However, this approach does not take into account correlations over time which are obtained in the time series approach.

There are existing studies that have used a combination of stochastic and time series approaches to take advantage of both approaches (e.g., [60]). However, when real-life information is lacking or EV charging profiles are derived from limited samples of EV data, the simulated results have a significant level of uncertainty and conclusions may be less valid.

2.5.2. HC studies in a Swedish context

The structure of the power grid and consumption habits can vary from country to country. Therefore, when comparing results, it is important to take into account the country in which the study was conducted. In the Swedish context, there are some studies investigating the impact of EV charging on the power grid (e.g., [49, 50, 57, 58]). For example, M. H. J. Bollen and S. K. Ronnberg [50] developed a tool to estimate HC for customers with EV and PV, and E. Mulenga et al. [49] used a stochastic approach to estimate the HC for both single-phase and three-phase charging.

Even at the national level, comparing results is difficult due to the use of different initial conditions and limits, resulting in different HC. Additionally, some studies place less emphasis on HC result and instead aim to illustrate a particular HC method (e.g., [50]). Others suggest examining additional distribution networks to obtain more general trends (e.g., [49]). With this in mind, conclusions from some of the Swedish studies are presented below.

Luthander et al. [57] studied an area with a rural and urban distribution grid, and simulated a fully electrified car fleet charging at 3.7 kW three-phase power. The results showed that the voltage level in the grid never exceeded the voltage drop limit of 10% of the reference voltage and that the minimum voltage was reduced more by EV charging in the winter than in the summer [57].

Mulenga et al. [49] studied two different distribution networks, where the HC of EVs was 73% respectively 100% of the customers charging simultaneously. The analysis was based on charging at 11 kW three-phase power and a voltage drop limit of 10%.

Hartvigsson et al. [58] conducted a geographical analysis on a national level to determine the effect of EV charging on Swedish LV grids. The study showed that the grid impact varied significantly based on the location of the LV grid and the charging strategy used. The findings suggest that city areas are more prone to experience power system violations than rural and urban areas.

2.5.3. Temporal resolution in HC studies

The temporal resolution of the time series used can impact the resulting HC. However, there is a lack of literature on what resolution is sufficient for different types of HC studies. In one study, the HC for PV in an Australian distribution grid was conducted and the results showed a significant difference between using 30-minute and 1-hour resolution [61]. Higher resolution data resulted in lower acceptance levels for PV implementation.

Another study investigated the impact of distributed PV systems on voltage levels in a Swedish distribution grid, comparing the results of using 10-minute and hourly averaging data [62]. It was concluded that the time averaging had a strong influence on the household electricity demand profile of individual households, but not as strong an influence on the voltage levels. There were however some variations in the 10-minute data that were reduced by the hourly data, particularly in the evening when large load fluctuations resulted in more varying voltage levels. However, it was suggested that hourly averages are sufficient for statistical investigations in voltage levels in the power grid, especially when evaluating voltage rise from PV.

A third study focused on a general method to reduce the computational burden of evaluating the HC for EVs based on voltage deviation, component loading, phase unbalance and harmonics [63]. The influence on different time resolutions was discussed, stating that the appropriate length of the time steps depends on the type of study being conducted. It was mentioned that a 1-hour resolution is the maximum acceptable length of a time step, as commercial and residential load profiles typically have this resolution. However, it is unclear for which type of study and which investigated PI this applies.

In this thesis, HC for EVs based on slow voltage changes and component overloading is investigated. Literature on how the time resolution affects this type of studies and maximum appropriate time step has not been found.

2.6. Research gap and contribution of the thesis

In previous research there are several studies investigating the HC for EVs, however there are some gaps in the research that this thesis aims to fill. Due to the differences in grid structure and people's habits in different countries, findings and conclusions derived from studies in other countries cannot be directly applied in Sweden. Therefore, it is valuable to conduct HC studies in a Swedish context. Furthermore, using a combination of HC assessment methods to evaluate the HC in combination with investigating the impact of different charging strategies and different implementation levels is not previously considered. Finally, many studies carry out analyses based on synthetic data. In the absence of real-life data, simulated results have a considerable degree of uncertainty, which leads to less meaningful conclusions. Therefore, presenting studies with a high degree of real-life information also contributes to filling the research gap.

Given the identified research gap, this thesis aims to evaluate the HC for EVs in Swedish residential areas and to examine how it varies depending on how the EVs are implemented and charged. The contribution of the appended papers are as follows:

- HC case studies reflecting conditions in Swedish residential power grids. The research is carried out in cooperation with a Swedish DSO. The analysis uses real-life power grid data, real-life residential electricity load profiles, and for Paper II, real-life data on EV charging behavior collected from a large number of chargers.
- The impact of the HC based on different EV implementation levels, PI limit used (Paper I) and charging strategies (Paper II) are evaluated.
- A combination of HC assessment methods is used. A deterministic approach to obtain the HC for the worst and best case EV implementation order (Paper I), a time series approach to account for the correlation of different loads over time (Paper I and Paper II), and a stochastic approach to account for uncertainties in EV charging location and behavior (Paper II).

3. Method and data collection

Different approaches for estimating the HC have been used in the included papers, however the overall method is similar. The overall method can be roughly divided into three steps as shown in Figure 5. The figure also includes information on the choices made and parameters used in each paper respectively.

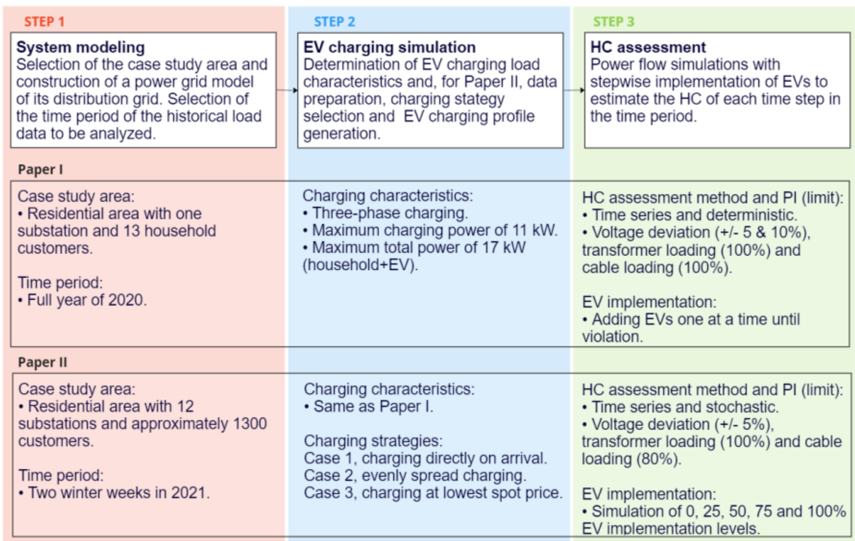


Figure 5. The overall method used in the thesis, with choices made and parameters used in each step for each paper.

3.1. System modeling

3.1.1. Case study area and distribution grid

The case study areas used in this thesis are located in the municipality of Borlänge, which is situated in the central part of Sweden. The local power grid in the municipality supplies electricity to approximately 30,000 customers and is owned and operated by the DSO Borlänge Energi Elnät. The power grid is fed from the regional power grid through HV/MV (high voltage/medium voltage) transformers and further distributed in substations equipped with MV/LV (medium voltage/low voltage) transformers. The voltage level on the LV side of the transformers can be adjusted by changing the number of windings in the transformer. Most of the MV/LV transformers in Borlänge Energi's grid do not have automatic on-load tap changing functions, and the transformer's winding ratio must be adjusted manually. Customers are supplied in a three-phase configuration, and most of the distribution grid consists of LV (0.4 kV) and MV (10.5 kV) cables.

The grid studied in Paper I consists of a MV/LV transformer and distribution cables feeding 13 detached single-family houses. This area was chosen because it is a residential area and hourly electricity consumption data was available earlier than in other parts of the grid due to early customer meter replacement. A much larger residential area, described more in detail below, was studied in Paper II. This area was chosen because it is a residential area, rather isolated from the rest of the power grid with only one outgoing MV cable to another area, and because of the availability of hourly electricity consumption data. The customers in the area consist mainly of individual single-family households, with some multi-family houses, and a handful of businesses and schools. The electricity grid does not have to cover the heating load because the area has district heating, which was designed when the area was planned in the late 1970s [64]. The structure of the power grid in the area is shown in Figure 6. It consists of two main feeding cables fed from the main power grid, 12 MV/LV substations and several distribution cables supplying electricity to approximately 1300 customers. In this thesis, the nodes consisting of the customer connection point, the cable cabinets and the cable joint are referred to as buses. In total, there are 1299 cables and 1278 buses in the power grid.

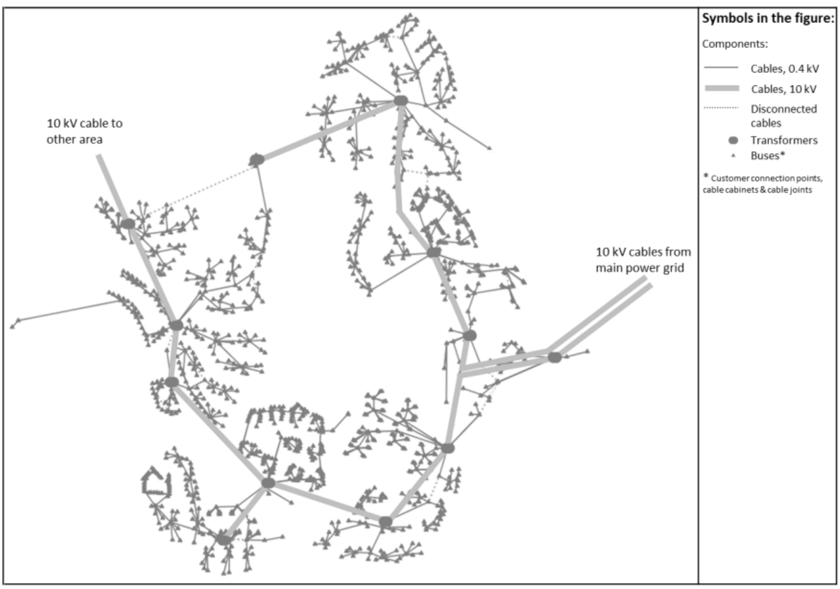


Figure 6. Structure of the power grid in the area studied in Paper II.

In both Paper I and Paper II, performance data and configuration settings for grid components, as well as information about the grid's structure, were extracted from Borlänge Energi's NIS. All transformers were modeled with a fixed voltage ratio between the primary and the secondary side, and the voltage level at the slack bus was set to 10.6 kV. The electricity is supplied to the customers in a three-phase configuration with a nominal phase-to-phase voltage of 0.4 kV.

3.1.2. Historical load data

The historical load data used in this thesis is on an hourly basis and consists of the total three-phase load, therefore a perfectly balanced load was assumed in the analysis. In Paper I, only active power load was considered, and data from the whole of 2020 was used in the HC analysis. In Paper II, both active and reactive power load was used and only two weeks of the year 2021 were used in the analysis. The reason for using a shorter time period in Paper II is due to the computational load, as a much larger area was investigated (13 customers in Paper I and just over 1300 in Paper II). The time period used in Paper II can be considered a worst-case scenario due to the high load on the power grid. This period consists of the two-week window when the highest aggregated electricity load in the area occurred, based on historical load data available from July 2021 to mid-January 2022. The aggregated active load distribution from the hourly measured meters in Paper II is shown in Figure 7.

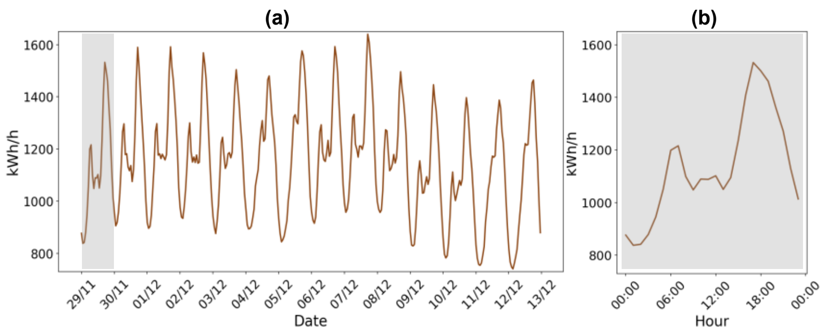


Figure 7. Aggregated active load distribution used in Paper II for hourly metered loads, (a) over the two-week period studied; (b) on the first Monday of the period.

Hourly loads were missing for a few customers and the outgoing 10 kV cable. These were instead implemented as static loads based on the Velander formula. The Velander formula calculates the aggregated power demand for customers based on their annual energy consumption and constants depending on the customer category [65].

3.2. EV charging simulation

3.2.1. EV charging characteristics

The EV charging was simulated as symmetrical three-phase loads with a power factor of 1. Three-phase charging was considered due to the significant and rapid increase in the number of BEVs in Sweden, with the majority of BEVs registered in 2021 being compatible with three-phase charging [6, 35, 66]. It was therefore considered to be a likely future scenario. Furthermore, a maximum charging power of 11 kW was set because the majority of newly registered BEVs in Sweden in 2021 are equipped with onboard chargers with a maximum capacity of 11 kW [6, 35]. The total load (historical load + EV load) was set at a maximum of 17 kW. If a residential customer's total power load exceeded 17 kW, the EV load will be reduced. A maximum of 17 kW was used as it corresponds to a main fuse of 25 A. The majority of households in the examined grids have 16 A main fuses but have the option of upgrading to 25 A without changing the connection cable to the house.

3.2.2. EV data

Real-life EV charging data was used in Paper II. The data was obtained from CTEK, a Swedish supplier of EV charging products [67]. The dataset includes chargers that are categorized as home chargers (located either at single-family or multi-family homes). All chargers are located in Sweden, but for privacy reasons, the exact location of the chargers was not known. The dataset included the following data:

- Date and time of EV plug-in and plug-out events, recorded in minute resolution
- Total energy consumed during each plug-in session (active energy, kWh)
- A unique charger-ID for each session

After data cleaning to remove erroneous data, the dataset included approximately 900 different chargers with a total of approximately 159,000 plug-in sessions. The dataset covers one year, ranging from 29 October 2020 to 29 October 2021, but not all chargers were active for the entire period. Data from nine different two-week periods were selected from the dataset and used in the analysis. The selection criterion was that they should be similar to the period used for the historical load (winter weeks without public holidays). The plug-in sessions were then rounded from the minute resolution to a 15-minute resolution to be used in the analysis. A 15-minute resolution was used to capture intra-hour events during EV charging. The historical loads in the area were measured on an hourly basis. Therefore, the same hourly power value was applied to all quarters within an hour for the historical load in the power flow calculations.

3.2.3. EV charging strategies and profile generation

In Paper I, charging behavior was not included, instead, a maximum charging power was set for all hours of the year. In Paper II, on the other hand, charging behavior was included and based on the real-life EV data (time of plug-in/out and energy consumption per plug-in session). Three different charging strategies/cases were considered to determine the time point of charging and the charging power at each time step in the charging profiles. The data from the plug-in sessions were used as constraints. The cases are summarized in Table 1.

Table 1. Summary of the different cases used in Paper II.

Case	Assumption of charging time point	Maximum charging power
1	Immediately on arrival	11 kW
2	Constant throughout the session	Average power of the session
3	Lowest spot price during the session	11 kW

Case 1 assumes that charging starts as soon as the EV is plugged in. Case 2 assumes that charging is evenly distributed throughout the plug-in session so that the charging power is constant from plug-in to plug-out. Case 3 assumes that EVs charge when the spot price is lowest during the plug-in session. In this case, the spot price information from SE3 has been used [68].

A charging profile was created for each of the nine time periods, each charger-ID and each case. All charging profiles from the same case were then placed in a charging profile pool. This resulted in three charging profile pools, each containing 4557 different charging profiles from 855 different chargers.

3.3. HC assessment

A power system analysis tool called Pandapower was used to construct the power grid models for the case districts considered and to conduct the simulations. This open-source tool, which has been validated and tested against commercial software, is based on the Python programming language and includes a Newton-Raphson power flow solver [69, 70].

Combinations of HC assessment methods have been used in this thesis. Both included papers use the time series approach in combination with another method. The time series approach was chosen because it accounts for the dynamic nature of different loads and includes the correlation of different loads over time. This approach allows for the inclusion of differences in the HC during different seasons and times of the day (Paper I) as well as the time-dependent behavior of EV charging (Paper II).

In Paper I, the simulations were carried out on time series of historical load data and the implementation of EVs was based on a deterministic approach. For each time step (1 h) within the selected time period (1 year), the maximum EV charging power was added from one EV at a time until a violation occurred. The number of EVs charging simultaneously during the initial violation was recorded for each time step. These results were then compiled to generate an annual representation indicating the number of hours per year that a specific quantity of EVs was charging at the time of the first violation in the grid. The analysis was repeated for two different limits of the PI of the voltage deviation, 5 and 10%, and for two different priority lists of the EV implementation order, “worst case” and “best case”. These priority lists were based on the voltage drop experienced by the customers. In the worst case, EVs were added in order of priority, starting from the customer experiencing the highest voltage drop and progressing to the customer experiencing the lowest voltage drop. The sequence was determined under a load configuration where each customer received an equal amount of load. The best case priority list followed the reverse order of implementation. The deterministic approach for EV implementation was chosen in this paper to show the differences in the best case and worse case implementation order of EVs in the area.

In Paper II, the time series approach was used in combination with a stochastic approach. The time series approach was used by running simulations for each time step in the period using historical load data and EV charging profiles. A stochastic approach using MC simulations was used to determine the location of a charger and the charging profile to be used. This was done by randomly assigning charging profiles from the charging profile pool to randomly selected households. Power flow simulations were then performed for all time steps in the time period. The analyzed time period consisted of 1344 time steps (one every 15 minutes) and the MC simulation was repeated 200 times. The number of customers receiving a charger was based on four predefined implementation levels (25%, 50%, 75% and 100% EV implementation) and the MC simulations were performed for each implementation level and each charging strategy/case. The stochastic approach was chosen in Paper II because it accounts for uncertainties in the HC analysis, here in terms of EV implementation location and individual charging behavior.

An overview of the HC assessments used in the papers is shown in Figure 8.

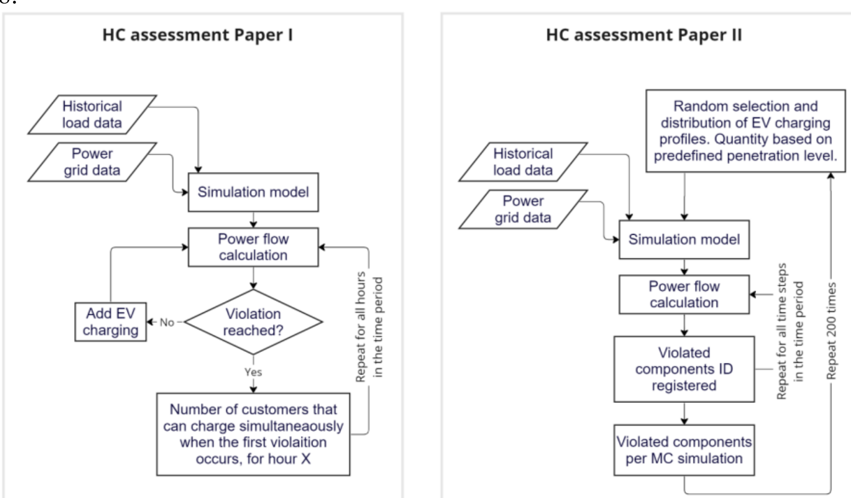


Figure 8. Overview of the HC assessment used in Paper I and Paper II.

3.3.1. Investigated PI and PI limits

In this thesis, three different PIs have been considered; cable loading, transformer loading and voltage deviation. According to the Swedish regulation EIFS 2023:3, the 10-minute rms (root mean square) value of the voltage should be within ±10% of the nominal voltage [11]. Due to limited data availability, the simulations in this thesis were performed based on hourly values of the historical electricity load. Furthermore, regarding the voltage limit, the DSO in this study wants to keep the voltage within a stricter limit of ±5% to avoid disturbances for the customers. Therefore the stricter limit of ±5% was used in Paper II and both limits were used in Paper I to compare how the HC was affected.

The PI limit used for the transformer loading was set at 100% of the rated power. The cable loading was based on its rated current and was set at 100% (Paper I) and 80% (Paper II). The lower limit was set to better reflect reality, as the actual utilization of a cable can be lower than its rated current. The utilization is dependent on several factors, such as temperatures, cable placement, voltage drop, short circuit characteristics and fault clearance [71].

4. Result

4.1. EV charging profiles

The statistics derived from the charging profile pools give an indication of people's home charging behavior. The mean energy consumption was approximately 10 kWh per plug-in session and the mean duration was around 13 hours. The charging frequency was on average around 11 plug-in sessions over a two-week period. The number of chargers plugged in at midnight was approximately double the amount plugged in at midday, as shown in Figure 9. The figure shows the proportion of chargers in the charging profile pool with an EV plugged in. Figure 9 (a) is based on the two-week periods and Figure 9 (b) shows the first Monday in the time period in a zoomed-in view.

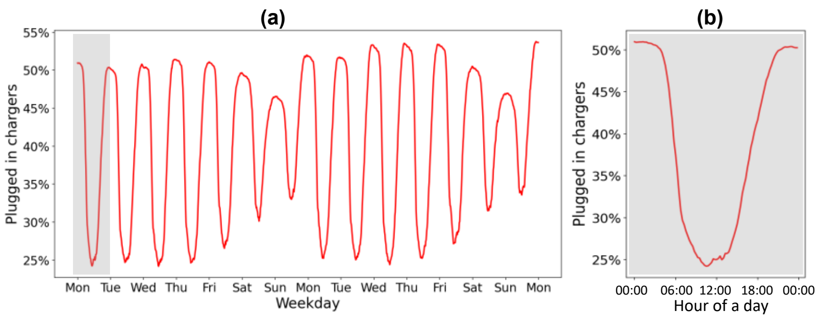


Figure 9. The proportion of chargers in the charging profile pool with an EV connected, (a) for the two-week periods, (b) for the first Monday in the periods.

When and at what power level an EV was charged varied a lot between the three different cases. This is illustrated in Figure 10, which shows the resulting charging profile for a charger over a two-week period for all three cases. Case 1 and Case 3 have high charging rates compared to Case 2, where the charging is evenly distributed throughout the entire plug-in session. In Case 1, charging starts immediately after the EV is plugged in and in Case 3, the charging takes place during periods of low electricity prices.

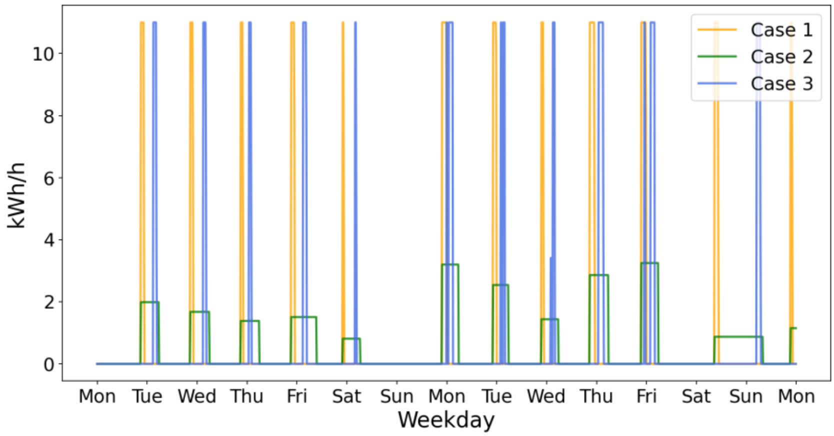


Figure 10. Charging profiles for all three cases for one example charger.

Figure 10 illustrates the usage pattern of a single charger, but to see trends across multiple users, aggregated results are visualized. The average charging profile per charger for each case is shown in Figure 11. It is the aggregated load of all profiles in a pool divided by the total number of chargers in a pool. The aggregated peak loads of Case 3 are significantly higher compared to the other cases. This is because the charging loads of several EVs are shifted into the same low electricity price period. Case 1, on the other hand, has a flatter aggregated charging profile due to the diversity of arrival times and therefore different charging start times.

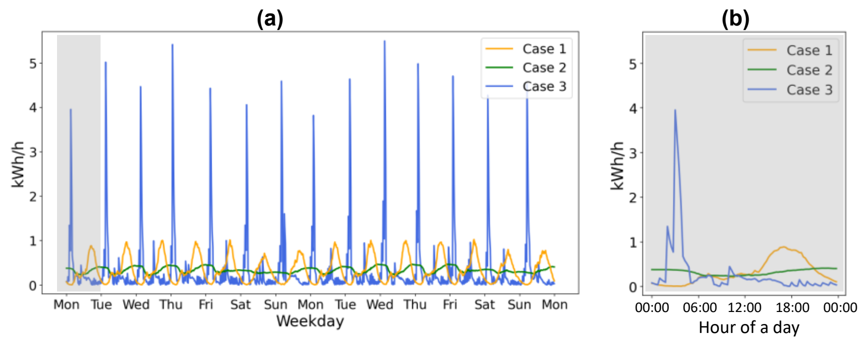


Figure 11. Average charging profile per charger and case, (a) for the two-week periods, (b) for the first Monday in the periods.

How the aggregated charging loads coincide with the household load is illustrated in Figure 12. It shows the average charging profile together with the average of the historical household load for the hourly metered households in Paper II.

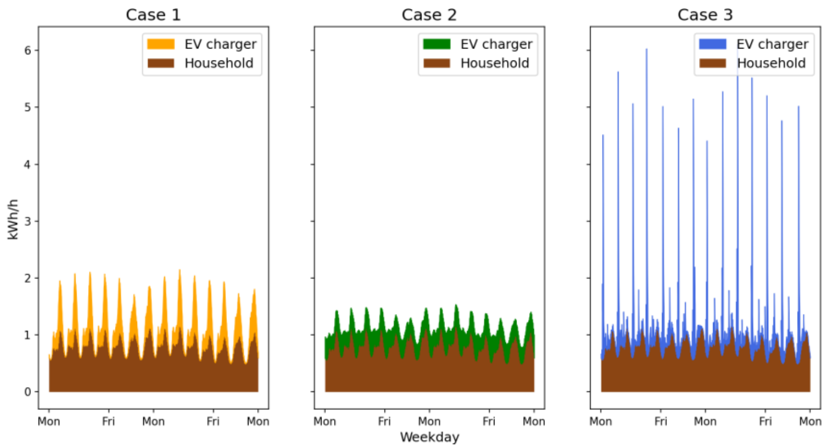


Figure 12. Average load profile per charger and average historical household load for Paper II.

The peak loads from the charging coincide with the peak loads from households when EVs are charged directly on arrival, i.e. Case 1. For the other two cases, the peaks do not coincide, but for Case 3, new, much larger peaks are created. This is because many EVs charge at exactly the same time, in response to the low price signal.

4.2. HC results

4.2.1. Impact of charging strategy and EV implementation level

The findings presented in this subchapter are derived from Paper II. When no EV load was simulated, i.e. when calculations were based only on historical load data, very few violations occurred in the grid. Solely two buses and one cable were violated, and they were violated at every time step of the simulation. When presenting the statistics of the results of the EV simulations, the violations from these three components are excluded to give more representative values.

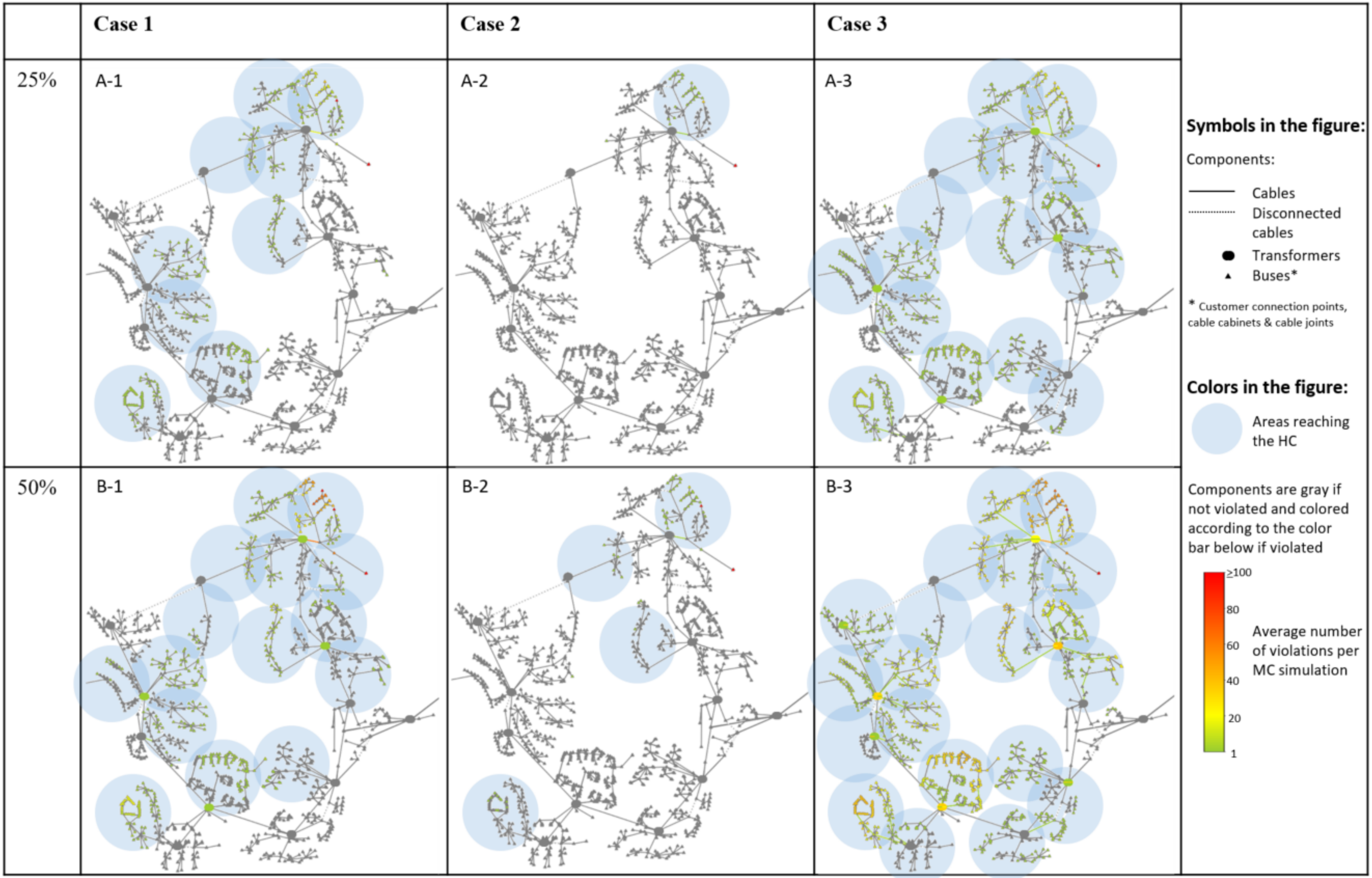
The results in this section are based on 200x1344 simulations for each case (200 MC simulations with 1344 time steps in the two-week period). Results are based on PI limits of 5% voltage drop, 100% transformer loading and 80% cable loading. The number of unique components violated for each case and implementation level is shown in Table 2. The numbers in parentheses show how often, on average, a unique component was violated per simulation set.

Table 2. The number of unique components violated for each case and EV implementation level. (In parenthesis, the average number of times a unique component got violated per MC simulation).

Violated component	**EV implementation level**	**Case 1**	**Case 2**	**Case 3**
CABLES	25%	2 *(14.2)*	2 *(0.1)*	11 *(1.5)*
	50%	3 *(32)*	2 *(1.2)*	59 *(1.6)*
	75%	9 *(16.2)*	2 *(6.5)*	97 *(4.5)*
	100%	20 *(11.0)*	2 *(20.7)*	119 *(9.6)*
TRANS-FORMERS	25%	0 *(-)*	0 *(-)*	4 *(1.3)*
	50%	4 *(0.2)*	0 *(-)*	7 *(17.8)*
	75%	4 *(3.6)*	0 *(-)*	9 *(23.3)*
	100%	4 *(23.7)*	0 *(-)*	10 *(32.1)*
BUSES	25%	281 *(1.8)*	33 *(1.2)*	588 *(2.2)*
	50%	453 *(5.9)*	61 *(2.2)*	986 *(11.8)*
	75%	577 *(13.1)*	103 *(3.4)*	1121 *(24.5)*
	100%	698 *(23.6)*	143 *(5.5)*	1193 *(36.9)*

As can be seen in the table, there is a large difference in how the grid is affected depending on the case and the implementation level. For example, an implementation level of 25% results in more violations for Case 1 and Case 3 compared to Case 2 with an implementation level of 100%. In Case 2, the increase in implementation level of EVs does not affect the number of violated cables or transformers, but the number of violated buses increases. A relatively large number of cables are violated in Case 3 compared to the other two cases. The majority of the violated cables were 0.4 kV cables. 10 kV cables were only violated in the absolute worst case and implementation level (Case 3, 100%), where five of the 119 violated cables were 10 kV cables.

The results, represented as maps of the grid, are shown in Figure 13. In this figure, the problem areas in the grid can be derived. It can be seen that for higher implementation levels there is an increase in both the number of areas affected and the number of violations in the areas already affected. Case 3 has the highest impact on the grid, followed by Case 1 and Case 2.



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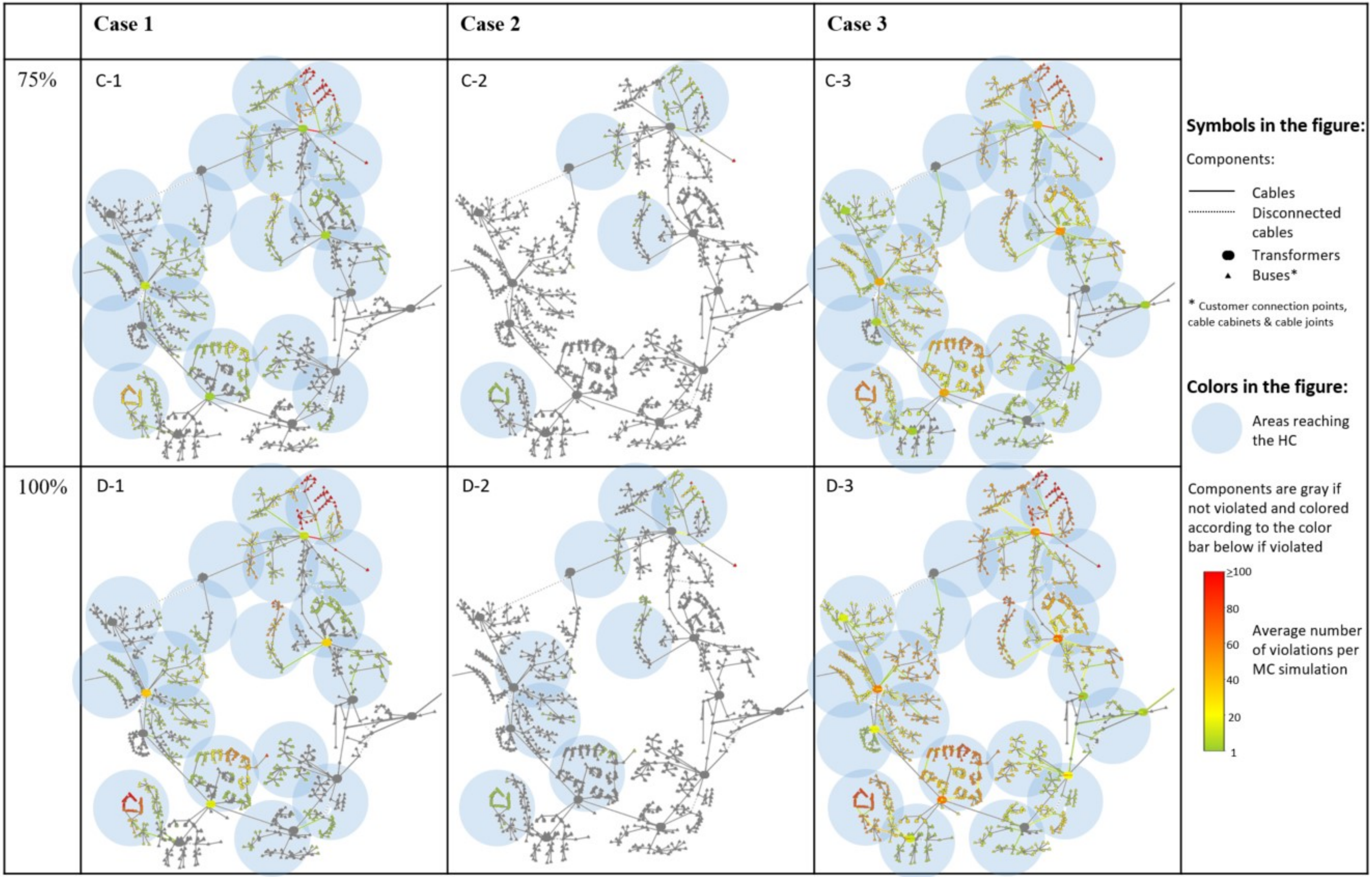

Figure 13. Grid illustration of areas reaching the HC and the average number of violations per MC simulation. For all cases and EV implementation levels of 25, 50, 75 and 100%.

4.2.2. Impact of PI limit and EV implementation

In Paper I, the impact of different limits on the voltage PI was investigated, as well as the location of EV implementation. The results can be seen in Figure 14, which shows the proportion of hours in a year with violations for a given number of EVs charging simultaneously.

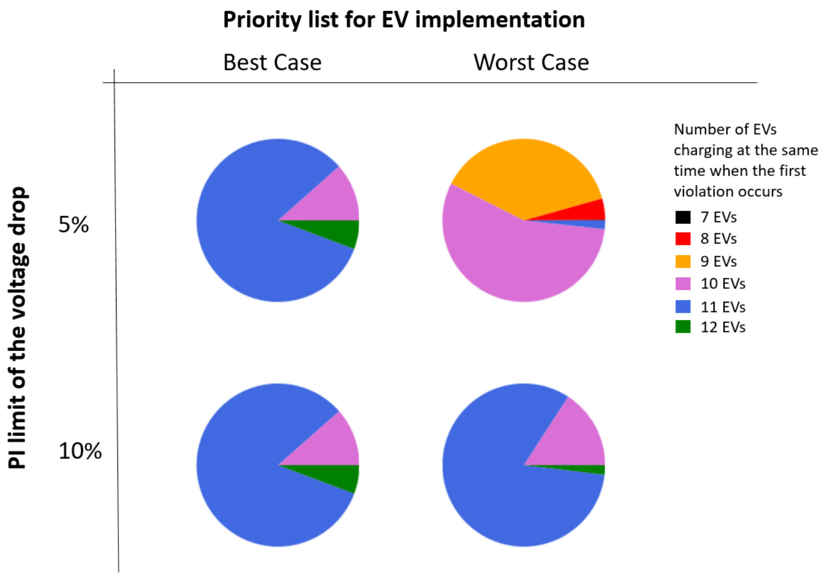

Figure 14. The proportion of hours in a year with violations for a given number of EVs charging simultaneously, from Paper I. Each pie chart displays the result from a specific setup of the EV implementation order and the PI limit of the voltage drop.

As shown in Figure 14, for the two best case EV implementations, 11 customers were charging at the same time for about 80% of the hours in the year, when the first violation occurred. Similar results are shown for the best cases regardless of the voltage PI limit, as in both cases the cable loading was the limiting PI for most of the year. In the worst cases, the limiting PI was the voltage drop in the 5% limit case and the cable loading in the 10% limit case. Since the voltage was the limiting PI in one of the cases, using a less restrictive limit results in a higher HC, as shown in the figure.

A comparison of the impact of the voltage PI was also presented in Paper II, as shown in Table 3. As can be seen from the table, the less restrictive limit affects far fewer buses.

Table 3. Change in the number of buses violated when the voltage PI limit is changed from 5% to 10%.

Violated component	Imp. lev.	Case 1	Case 2	Case 3
BUSES	25%	281→2	33→0	588→48
	50%	453→5	61→0	986→360
	75%	577→16	103→1	1121→621
	100%	698→97	143→1	1193→893

5. Discussion

In the transition towards a decarbonized transport sector, the acceleration of EV deployment plays an important role. It is therefore important for the DSOs to gain insight into how this transition will affect their power grids and the potential for using the grids in a resource-efficient manner. These aspects are addressed in this thesis as it aims to investigate the HC of existing grids and explore its potential based on how EVs are implemented and charged. This in turn can indicate effective control signals for efficient power grid use. It can also provide insights into necessary future enhancement and serve as a basis for calculating their economic consequences.

The results of Paper II showed that changing the PI limit of the voltage deviation from 5% to 10% significantly increased the HC. However, as shown in Paper I, it depends on which PI is the limiting one. When the cable loading was the major limiting PI, there was almost no change in HC regardless of the change in the voltage deviation PI limit or the implementation order of the EVs.

Comparing the results of the two papers in terms of which PI was the limiting factor is difficult due to different initial conditions. Paper I used a cable loading limit of 100%, while Paper II used 80%. Additionally, the fixed voltage of 10.6 kV was set at different locations: at the MV side of the MV/LV transformer for Paper I and at the MV side of the HV/MV transformer for Paper II. Voltage drops in the MV cables cause lower voltage levels at the MV/LV transformers in Paper II, leading to a smaller marginal for the voltage deviation caused by EV charging.

In Paper II, varying HC for EV integration was observed depending on the charging strategy employed. However, all strategies were based on the same human behavior, with regard to EV energy consumption and plug-in/plug-out times, differing only in the setting of when the charging occurred. Therefore, significant differences in HC can be achieved based on the chosen charging strategy, without changing the human behavior. Spreading the charging over the plug-in session could accommodate a much larger proportion of EVs. This is in contrast to charging the EVs immediately upon plugging in, as the peak power of the EVs coincides with the peak power of the households. The least favorable strategy was to charge the EVs based on low spot prices. This resulted in a large number of EVs charging at high power at the same time, creating new and higher power peaks. Therefore, controlling the charging based on a single price signal, such as the spot price, could improve the power system at one level but worsen it at another. Similar findings are reported by Ashfaq et al., stating that system-wide services provided by EVs may cause problems in distribution systems, which could lead to conflicts of interest between TSOs and DSOs [8]. A combination of different price signals or coordinated charging control could therefore be useful. The introduction of power tariffs could have a smoothing effect locally, mitigating high power peaks and thus increasing the HC. According to Swedish regulations, DSOs are obliged to implement power tariffs by 2027 at the latest [24]. The effectiveness of such implementation depends, of course, on the design of the tariff and customer response.

One strength of this thesis is that it demonstrates the dynamic character of the HC. This aspect provides information for understanding the potential of EV implementation in a resource-efficient manner. The HC quantity varies over time, as shown by using a time series assessment approach, and also varies depending on how EVs are implemented and charged. The variety in HC based on EV deployment was presented with different deterministic implementation orders (Paper I) and by a stochastic approach accounting for uncertainties in the location of the implementation and charging behavior (Paper II). This diversity indicates the potential of existing grids to accommodate EVs with less reinforcement and also shows locations where reinforcement is likely to be needed with a larger EV car fleet.

Another strength of this work is the close collaboration with a DSO, which provides an industry-oriented perspective. This collaboration not only provides practical insights for the DSO but also contributes to the development of approaches that could potentially establish standard processes in the workflow of power system planning and grid enhancement. Furthermore, the analysis uses real-life data collected and measured in Sweden. Although the resulting HC is case-specific, the methods used and the results obtained contribute to insights into grid HC that reflect Swedish conditions in residential areas. Additionally, the analysis in Paper II is based on a significant dataset of EV chargers, which provides a natural distribution in individual charging behavior.

A limitation of using real-life data is however the assumption that the behavior is the same as in the dataset. For example, technological developments in EV battery sizes, policy implementation or external situations could potentially change the charging behavior of EV owners, leading to different results. Choices made in the modeling process also affect the result. The results are derived from three-phase charging, which may give a more optimistic HC. Results from another case study on Swedish grids indicate a higher HC for three-phase charging compared to single-phase charging [49]. Furthermore, the case study areas in this thesis have a district heating infrastructure. When district heating is used by a household, the electricity demand is generally lower than when electric heating is used (see Figure 2). Therefore, HC limitations could be more severe in areas without district heating infrastructure.

Another limitation is the time resolution used in the analysis. According to the voltage quality regulation, the 10-minute voltage values should be within +- 10% of the reference voltage [11]. In this thesis, hourly values of the historical load data and 15-minute EV charging data (Paper II) were used in the analysis. This could potentially overestimate the HC as more rapid voltage deviations that could lead to violations in a specific 10-minute interval are not captured. However, using a lower limit of the voltage deviation, 5% instead of 10%, resulted in a lower HC in comparison. Widen et al. suggested that hourly averages are sufficient for statistical investigations of voltage levels in the grid, particularly for PV implementation [62]. However they also noted that when a

10-minute average was used instead of an hourly average, the voltage level differed more in the evening. This could therefore have a greater impact on EV analysis as one of the charging strategies was to charge on arrival, which often occurs in the evening. Nevertheless, it is not known how much these simplifications affect the results and would require higher resolution data to investigate. However, this study has investigated the HC based on available data from the DSO and thus shows how it can be practically performed at the DSO. Future studies at the DSO may include higher resolution data as DSOs have started to measure 15-minute values for some customers, according to a new regulation [72].

6. Conclusions

In this thesis, the HC for EVs in residential power grids has been analyzed based on two different case studies. The analyses are based on real-life data to reflect the conditions in Swedish residential power grids. The work has been conducted in close collaboration with a DSO, which provides an industry-oriented perspective. In addition to providing insights for the research community, the work could provide a basis for DSOs to develop control signals for efficient power grid use. It also provides insights for future grid improvements and serves as a basis for economic assessments.

Different factors were considered in the analysis to gain an understanding of the variability in the potential of the existing power grids to accommodate EVs. The factors considered were the choice of charging strategy, the level of EV implementation, the location of EV implementation, and a change in the voltage deviation PI limit.

The PI that limited the HC varied depending on the PI limit used, where the EVs were implemented and the charging strategy used. An evenly spread charging strategy over the connection period resulted in almost no component violations regardless of the EV implementation level. A 5% voltage deviation limit resulted in a larger fraction of buses violated compared to the fraction of cables and transformers for all charging strategies. Furthermore, charging on arrival or at the lowest spot price resulted in a relatively high proportion of violated transformers for most EV implementation levels.

Paper I showed that when the voltage deviation is the limiting factor, the differences in charging location have a greater impact on the HC than when the cable load is the limiting factor. Therefore, when voltage deviation is the main concern in a grid, the location where the EVs are charged is more important as the voltage drop generally increases when a load is applied further out in the grid. Furthermore, the analysis showed that when the voltage deviation was the limiting PI, changing the limit from 5% (chosen by the DSO) to 10% (the legal limit) resulted in a significantly higher HC. Therefore, HC is highly dependent on the standards implemented by the DSO and is not solely an issue of the grid design and its electricity consumption/production.

The use of different charging strategies also had a significant impact on the HC. The strategies were based on the same charging connection behavior, differing only when the actual charging occurred. A charging strategy based on energy prices resulted in most grid violations due to the large number of EVs charging at the same time, resulting in new very high power peaks at times of low spot prices. The second worst strategy was to charge the EVs on arrival, as the peak power of the EV charging coincided with peak household demand. The best strategy from an HC perspective was when charging was spread over the plug-in session. This strategy resulted in fewer grid violations for a 100%

EV implementation compared to the other two strategies for a 25% EV implementation.

The extent of the residential grid where the HC is reached for different charging strategies and different EV implementation levels is presented in Table 4. It shows the ratio of violated components to the total number of components in the grid, providing a modified version of the data presented in Table 2 in the result chapter. A higher EV implementation level resulted in more violations for the buses in all three charging strategies. However, the number of overloaded cables or transformers was not affected by the EV implementation level when the charging was spread over the plug-in session.

Table 4. Extent of the residential grid where the HC is reached for a 5% PI limit of the voltage deviation. Given as a percentage of components violated for different EV implementation levels and charging strategies (from Paper II).

Violated component	**Imp. lev.**	**Case 1,** *Charging on arrival*	**Case 2,** *Evenly spread charging*	**Case 3,** *Charging at lowest spot price*
CABLES	**25%**	0%	0%	1%
	50%	0%	0%	5%
	75%	1%	0%	7%
	100%	2%	0%	9%
TRANS-FORMERS	**25%**	0%	0%	33%
	50%	33%	0%	58%
	75%	33%	0%	75%
	100%	33%	0%	83%
BUSES	**25%**	22%	3%	46%
	50%	35%	5%	77%
	75%	45%	8%	88%
	100%	55%	11%	93%

The analysis shows the potential for a more efficient use of the existing power grid based on different charging strategies. Maintaining charging power at a lower level and distributing it over time allows the grid to accommodate more EVs. Conversely, if a significant number of EVs charge simultaneously or during peak demand periods of other grid equipment, the grid's capacity to accommodate EVs is significantly reduced. This underlines the necessity for implementing coordinated charging controls for EV fleets or introducing power tariffs to avoid power peaks and thus increase the HC of the power grids.

7. Future research

As a continuation of Paper II of this thesis, an additional analysis is in progress. The same case study will be used, but this time the impact of both EV charging and local production from rooftop solar PV will be included in the HC analysis. The reason for including PV in the analysis is the increasing popularity of the technology. The feed-in of PV production can cause too high voltage levels locally in the grid, in contrast to EV loads, which can cause too low voltage levels. The analysis will therefore investigate how the HC is affected with both technologies present in the grid, and to what extent they can synergize. The analysis will integrate intelligent EV charging controls into the model to develop new charging strategies.

In addition to the aforementioned study, the exact direction for the rest of the doctoral studies is still undecided, and several options are being discussed. One option is to investigate how a centralized charging control could be designed and operated. For example controlling the charging based on the voltage level at the customers. There will be technical challenges in this work, such as the design of the control mechanism and how to practically implement it. There would also be challenges related to the acceptance of such control and how to create fair and feasible incentives for using it. The motivation for conducting this option is to understand how such control should be designed to improve the HC and avoid unnecessary reinforcements of the grid. Furthermore, as the PhD studies are conducted at a DSO, it is a good opportunity to delve deeper into how this could be implemented in practice and the DSOs role in this.

A second option is to investigate the causes of the grid violations, what alternatives there are to increase the HC, and to make economic assessments of the alternatives. Findings from this option could contribute to more cost- and resource-efficient grid upgrades.

A third option is to carry out analyses for other types of areas. For example similar studies in residential areas without district heating or studies in industrial areas as well as simulated DC fast charging. This would help to understand how and if the findings of this thesis differ for other types of areas, and thus provide further input for DSOs to develop efficient control signals.

In addition to the options mentioned above, there are discussions about whether batteries, vehicle-to-grid (V2G) or other demand response technologies should be included in future analyses.

The options given for the continuation of the study are somewhat different, with different approaches and methods to be used. However, there is a common denominator between these options and the doctoral studies as a whole. The idea is to conduct research with an industry-oriented perspective, providing methods and results that can be applied by market stakeholders. Additionally, the ambition is to conduct research that contributes to making power grids an enabler, rather than an obstacle, in the transition of the energy system.

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