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Photovoltaics and opportunistic electric vehicle charging in the power system – a case study on a Swedish distribution grid

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Abstract: Renewable distributed generation and electric vehicles (EVs) are two important components in the transition to a more sustainable society. However, both pose new challenges to the power system due to the intermittent generation and EV charging load. In this case study, a power system consisting of a low- and medium-voltage rural and urban distribution grid with 5174 customers, high penetration of photovoltaic (PV) electricity and a fully electrified car fleet were assumed, and their impact on the grid was assessed. The two extreme cases of two summer weeks and two winter weeks with and without EV charging and a PV penetration varying between 0% and 100% of the annual electricity consumption were examined. Active power curtailment of the PV systems was used to avoid overvoltage. The results show an increased electricity consumption of 9.3% in the winter weeks and 17.1% in the summer weeks, a lowering of the minimum voltage by one percent at the most, and a marginal contribution by the EV charging to lower the need of PV power curtailment. This shows the minor impact of EV charging on the distribution grid, both in positive terms of allowing more PV power generation, and in negative terms of lower voltage levels.

1 Introduction

The global market for photovoltaic (PV) power generation has increased rapidly in the recent years. Although the contribution of PV power generation in 2017 was merely 2% of the global electricity demand, the share of PV is significantly higher in several countries and regions [1]. Traditionally, the power generation from large centralized power plants is regulated to match the varying load in the power system. With the introduction of intermittent generation such as wind and PV power, new challenges for the power system arise such as larger voltage fluctuations [2]. At the same time, the recently started transformation of the transportation sector from fossil-fueled vehicles to electric vehicles (EVs) will also affect the power system due to the high charging power [3].

Both EV charging ports and PV systems are mainly connected to low-voltage (LV) or medium-voltage (MV) distribution grids, which are designed to handle unidirectional power flows from the high-voltage transmission grid to customers. The distribution grid is therefore designed to handle the voltage drop along the distribution feeders before reaching the customer [2]. Higher loads such as EV charging lead to higher currents in the feeders and thus larger voltage drops [4]. On the other hand, consumers with roof-top mounted PV systems can also be micro-producers, so called prosumers [5]. The intermittent PV power generation makes it necessary for the distribution grid to handle bidirectional power flows. For customers far away from substations, a combination of high generation and low load might lead to voltage levels exceeding the acceptable limit, and a combination of low or zero generation and high load might lead to too low voltage [2, 6, 7]. The combination of PV power generation and EV charging might, however, also be beneficial if charging occurs at the same place and time as the PV power generation, in which case the voltage might stay within limits. Therefore, a case study on a real distribution grid with both high penetration of PV and EVs is relevant to assess how voltage violations are affected.

1.1 Related work and motivation

There are several research papers in the field of overvoltage analysis due to PV power generation in the distribution grid. Solutions to prevent overvoltage include grid reinforcement [8], distributed energy storage [9, 10], active and reactive power control by PV inverters [8, 11, 12], active voltage control at the MV/LV transformer stations [9, 13], and demand response of household loads [14]. An overview of methods and strategies for overvoltage prevention in distribution grids with high shares of PV power is provided in [15]. Reinforcement of the power grid is a common solution to comply with the grid codes, for example to keep the voltage within acceptable limits [8]. Grid reinforcements are however associated with high costs, which might make other solutions more cost-effective [15]. Voltage control with on-load tap-changing transformers requires real-time measurements at several nodes in the low-voltage grids [9]. Furthermore, many MV-LV transformers do not have automatic on-load tap changing functions, instead the winding ratio has to be adjusted manually. Given the high variability of PV generation, this would be too time-consuming and expensive.

According to the power-quality standard EN 50160, the voltage at each customer should be within $\pm 10\%$ of the rated voltage [16]. This implies that PV inverters might have to switch off during periods with high PV power generation and low load, if the local voltage reaches 110% of the rated voltage. In Germany, where the rapid expansion of PV installations has led to high PV penetration locally in distribution systems, PV systems with an installed power lower than 30 kW either have to limit their output to 70% of the installed capacity or install an inverter with remote power control available to the system operator [7]. PV systems larger than 30 kW must be controllable remotely [7]. A fixed feed-in limit may, however, lead to unnecessary production losses in areas with low PV penetration, alternatively still lead to overvoltage in areas with high PV penetration. Remote control of the inverters requires extra communication and measurement equipment. In this study, curtailment of active power will be used as a method to avoid overvoltage. However, instead of using a fixed limit for the power output, a dynamic limit – similar to the droop based active power curtailment in [12] – is applied to the PV systems. With this scheme, the output power of the inverter is locally controlled by the voltage at the prosumer without any need for remote control of the PV inverters.

Possible solutions to avoid too low voltage levels, i.e., less than –10% of the rated voltage, include grid reinforcement, automatic on-load tap-changing transformers and demand response. Electrical energy storage can also be used if the power consumption has large variations during the day, and the storage capacity is enough to compensate for the high load when required. However, this study does not include any of these alternatives, and thus only examines if undervoltage occurs and the number of customers affected.

If no remote control equipment or automatic on-load tap-changing transformers for voltage control are present – which is the case in many MV-LV distribution grids – a voltage disturbance in one LV grid will affect surrounding LV grids as well. Reverse power flows in the MV grid caused by high PV power generation in the LV grids will increase the voltage in several MV nodes, which will lead to high voltage levels for a large number of customers. It is, therefore, important to study the effects on a wider scale than on just one LV grid.

Studies on the effects of EV charging on the distribution grid are more scarce than studies of PV power generation in the distribution grid. Previous research in the field has focused on only one or a few LV grids [17–19]. In [17], active power limitation of EV charging and reactive power control were used to avoid violating the voltage boundaries in a LV grid. In [18], a tool to simulate the grid impact from EV charging (3.7 kW and 22 kW) and distributed generation (DG) in LV grids was developed. Smart EV charging, grid reinforcements and energy storage were compared, and energy storage in combination with smart charging were found to be suitable to compensate for both high EV charging demand and high PV power generation [18]. In a remote LV grid, voltage violations were found to occur before grid components were overloaded when the peak power demand was increased [18]. Energy storage was also used in [19] as a tool for voltage management in a LV grid with EV charging and DG.

Previous studies on the combination of EV charging and PV electricity production have focused on only one or a few LV grids, whereas studies on large distribution grids are lacking in the literature. As mentioned before, it is relevant to examine the effects on a wider scale than just a few LV grids. Therefore, this study advances the knowledge about the combination of EV charging and PV electricity production by examining the effects on a large MV-LV distribution grid.

1.2 *Aim and structure of the paper*

The aim of this paper is to study the hosting capacity for PV power in a large distribution grid, and how this is influenced by adding EV charging load to the existing customer load. A distribution grid in the municipality of Herrljunga, Sweden, with 5174 customers was used for the case study.

This paper continues on a previous study on the same distribution system, which addressed the problem with overvoltage due to high PV power generation [20]. The aim of that study was to develop a methodology to determine the required storage capacity and need for power curtailment of PV systems to avoid overvoltage. In this study, EV charging is added to the electrical loads to study the temporal correlation between the PV power generation and the EV charging. This makes it possible to quantify how both EV charging and PV power generation affect the power grid in terms of required PV power curtailment and voltage levels for the customers.

In this paper, opportunistic EV charging from the grid with moderate charging power is assumed, i.e., the EVs are charged whenever parked until they are fully charged or depart. We consider this to be realistic and convenient, since it represents a case where people are not willing to adjust the charging of the EVs to what is happening in the rest of the power grid. Achieving large-scale smart-charging of electric vehicles, in terms of reducing the charging power when the voltage is too low or shifting the charging to periods with low demand and high generation, will most likely need incentives for the users. Fast-charging high-power stations are likely to be located closer to existing large infrastructure such as city centers or highways than home-charging stations with lower power would be. However, the distribution grid is likely to be stronger in urban than in suburban or rural areas. Therefore, moderate-power charging of 3.7 kW (16 Ampere single-phase) distributed among all houses and parking lots is of highest interest for this study. Although one-phase EV charging was used for the modeling, the charging power was evenly distributed on all phases to match the existing load data from the electricity meters. This assumption decreased the impact of the extra EV charging load on the distribution grid and represented a conservative scenario.

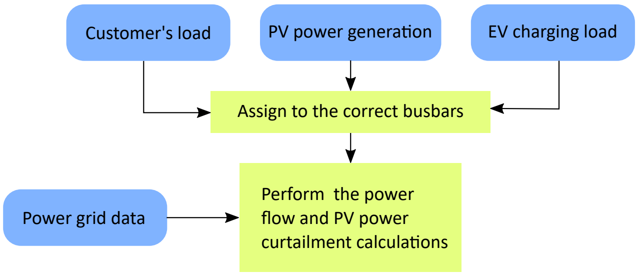

Fig. 1: Outline of the simulation algorithm.

This paper is an extended version of the conference paper 'Photovoltaics and opportunistic electric vehicle charging charging in a Swedish distribution grid' presented at the Solar Integration Workshop in Berlin, Germany, in 2017 [21]. In comparison to the conference paper, several parts are rewritten, new methodology is added and the results and conclusions are revised.

The paper is organized as follows: Section 2 presents the data for the power grid, PV power generation, electricity consumption and EV charging, and the methodology for calculating the power flow and PV power curtailment. Section 3 presents the results for voltage, current and power fluctuations and how these values are affected by PV power generation and EV charging. In Section 4 the consequences and limitations of the findings are discussed, and Section 5 presents the main conclusions of the study.

2 Methodology and data

This section describes the data for the study, the power flow and PV power curtailment algorithms and the EV charging model. An outline of the methodology and data is shown in Fig. 1.

2.1 *Power grid data*

The power grid in Herrljunga municipality consists of a three-phase MV/LV grid with 5174 customers, distributed over 3891 grid connections in 338 LV grids. A scheme can be found in Fig. 2.

The power grid covers both a rural area as well as two small city areas. Hourly power consumption data were available for each customer during a whole year. However, only two weeks in the winter and two weeks in the summer with large mismatch between load and generation were considered due to the available EV charging data, see Section 2.5. All grid properties such as wire thickness and material, length of the lines and impedances were known. The rural part of the power grid has a radial structure, whereas the power grid in urban areas has more interconnections.

With the impedance for every feeder in the system being available, it was possible to calculate the voltage and current in every part of the grid. According to the standard EN 50160 the mean 10 minutes rms of voltage magnitude variation must be within ±10% for 95% of the time. However, a number of countries have national requirements that deviate from EN 50160; for example Sweden requires the same allowed voltage range but for 100% of the time [22]. Since surplus PV generation fed into the grid increases the voltage, the inverter has to either reduce the power or switch off not to violate the upper voltage limit.

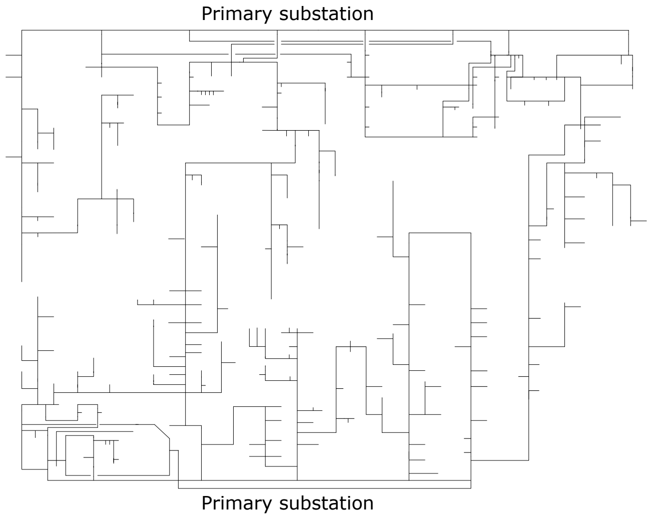

Fig. 2: Outline of the MV grid with all feeders. The two city areas are in the upper right and lower left corners.

2.2 *Electricity consumption data*

Electricity consumption data for the whole year 2014 for all customers, such as detached houses, apartments, offices, small industries and farms, were obtained from the distribution system operator Herrljunga Elektriska. All except four customers were connected to one of the 338 LV grids in the MV grid area. The studied periods were Monday January 13th to Sunday January 26th and Monday July 21st to Sunday August 3rd 2014. These two periods were chosen to examine two periods; one of high electricity load and low PV power generation (winter), and one of low electricity consumption and high PV power generation (summer).

2.3 *PV power generation data and scenarios*

The PV power generation data were calculated on an hourly basis with irradiance data for 2014 from the STRÅNG model, developed by the Swedish Meteorological and Hydrological Institute (SMHI) [23]. The methodology for calculating the PV power generation used for this study is thoroughly presented in [24]. Light Detection And Ranging (LiDAR) data were used to create a digital surface model (DSM) of the rooftops in the studied area with a pixel size of 2×2 m^2. The annual solar irradiance of the building DSM was then computed using the built-in tool Solar Analyst in ArcGIS [25]. Rooftop segments with irradiation exceeding 800 kWh m^{-2} yr^{-1} were considered suitable for PV installations.

For each category the hourly solar irradiation was computed using standard methods for conversion of horizontal to in-plane irradiation, including the Hay and Davies model for diffuse radiation [26]. A constant albedo of 0.2 was assumed and a constant PV system efficiency of 15% was used.

The PV penetration was defined as the yearly accumulated PV electricity generation as a share of the yearly electricity demand within the grid area. For the PV penetration estimation, the additional electricity consumption due to EV charging data were not included.

Rooftops suitable for PV installations were selected randomly until the PV penetration reached 10%, and thereafter additional PV systems were added until 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% penetration were reached, in total 10 simulations. Each simulation contained the two winter weeks and the two summer weeks chosen for the study. This was done 10 times, each of them with a different selection of rooftops, to get a more representative result for different spatial distributions of the PV systems than if only one distribution would have been considered.

2.4 *Power flow and PV power curtailment*

A large majority of all buildings in Sweden, including detached houses, have three-phase connections. However, electric load data per phase for every customer in the studied power grid were not available [20]. Therefore, a perfectly balanced three-phase power grid was used in the power flow simulations, which were all done in MATLAB.

Hourly values of PV power generation and load were used for the power flow simulations, which means that there might be shorter periods of even higher or lower voltage levels. However, due to the smoothing effect of aggregating loads, the sub-hourly power fluctuations of aggregated electric loads within an LV grid are generally smaller than the fluctuations of individual household loads [28]. The highest voltage levels occur during times with the highest irradiance, i.e., clear sky irradiance during noon, and low power demand. During these periods, the PV power generation is already close to maximum potential and the load is low, and therefore there would be a low risk of significant sub-hourly voltage spikes due to lower load or higher generation. This means that hourly data for a large distribution grid give a reliable estimate of the voltage fluctuations.

The feed-in power of the inverters depended on the local voltage at the connection point and was adjusted according to this. The droop based active power curtailment method described in [12] was slightly adjusted, for example with new voltage limits and correction for the maximum curtailment to allow self-consumption.

For each prosumer, the net power generation P_t^{net} for every time step t was dependent on the voltage V_t as

$$P_t^{net} = \begin{cases} P_t^{PV} - P_t^{load} - m \times (V_t - V_{lim}) \\ \qquad \text{if} \quad V_t > V_{lim} \quad \text{and} \quad P_t^{PV} > P_t^{load} \\ P_t^{PV} - P_t^{load} \qquad \text{otherwise} \end{cases} \tag{1}$$

where P_t^{PV} is the PV power, P_t^{load} is the customer load including the EV charging, m is a slope factor (Watt/Volt) and V_{lim} is the voltage limit above which the power to the grid is curtailed. Each PV system was assigned its own slope factor m, calculated as

$$m = \frac{P_{PVmax}}{V_{max} - V_{lim}} \tag{2}$$

where P_{PVmax} is the maximum PV power from each system and V_{max} is the maximum allowed voltage. The maximum allowed voltage V_{max} was set to 1.10 pu as in the voltage quality standard EN 50160. The lower voltage level for power curtailment V_{lim} was set to 1.05 pu, i.e., half of the rise of V_{max}. An upper limit of 1.05 pu was used in, for example, [6, 10] where LV grids were studied.

The PV power P_t^{PV} could not be curtailed below the customer load P_t^{load}. Based on the results from (1), the power actually going to or from the grid P_t^{grid} was calculated according to

$$P_t^{grid} = \begin{cases} P_t^{net} & \text{if} \quad P_t^{net} > 0 \quad \text{or} \quad P_t^{PV} < P_t^{load} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

which means that self-consumption of the PV power was favored. The active power curtailment losses P_t^{losses} at time t for each PV system were calculated as

$$P_t^{losses} = \begin{cases} P_t^{PV} - P_t^{grid} - P_t^{load} & \text{if} \quad P_t^{PV} > P_t^{load} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Since the active power curtailment method was based on the local voltage, PV systems far from the substations generally had to curtail more of the PV power production. Moreover, the power curtailment also depended on the installed power of the surrounding PV systems, especially within the same LV grid. However, power production –

or consumption – in one LV grid also affected the surrounding LV grids by the increasing voltage in the MV grid, since all MV/LV transformers had fixed winding ratios.

The active power curtailment was calculated with an iterative algorithm to find a stable solution for each hour. In the first iteration voltage levels with the maximum possible PV power (P_t^{PV}) were calculated, which for high PV penetration levels resulted in high voltage for the customers. In the next iteration, the PV power was set according to (1) for each PV system. The subsequent load flow simulation resulted in new voltage levels. The iterations were continued until the algorithm found a stable solution without overvoltage for any customer.

2.5 *Electric vehicle charging model*

The EV charging model was used to calculate time series of power consumption at each customer bus in the power grid. The model, described in [29], is based on a non-homogeneous Markov chain, which is a stochastic process $\{X_t\}_{t=0}^{\infty}$ where the probability of transitioning from one state to another does not depend on the history of previous states [30]:

$$\begin{aligned} &P(X_{t+1} = j | X_t = i, ..., X_2, X_1) = \\ &P(X_{t+1} = j | X_t = i) = p_{ij}(\delta) \end{aligned} \tag{5}$$

where $p_{ij}(\delta)$ is the probability to transition from state i to state j at time group δ. Both i, j belong to state space $S = \{1, 2, 3, ..., M\}$ with M states. In the EV charging model, the states of the Markov process represented the parking locations, which were defined as $S = \{$"Home", "Work", "Other"$\}$. The state "Other" referred to public parking lots that were neither residential nor workplaces.

All the transition probabilities, between the three states S, could be written in the form of matrices $T(\delta) = (p_{ij}(\delta))_{3\times3}$ with a time step of one minute. The time group δ varied based on the minute of the day during which the transition was taking place and whether the day was a weekday or a weekend. Thus in total there were 1440×2 transition matrices. Transition probabilities were estimated using the methodology presented in [31] and using the data from [32]. Since the load data for the customers were only available with an hourly resolution, the EV charging data were averaged over each hour. The model in [29] was validated using data for driving patterns in Sweden.

Charging at each parking state S represented charging profiles for residential, workplace, and public, arranged respectively with the states. The public charging profile represented the charging profile in the city centre; namely in non-residential and non-workplace locations, e.g., shopping centers and leisure locations. The municipality of Herrljunga contained 5295 vehicles as of the year 2016 [33]. Depending on the type of the electricity customers, each of them was considered to follow a parking state. There are no official statistics on the number of parking spaces in the city, therefore it was assumed that there were 1.7 and 1 parking spaces per detached house and apartment, respectively. The city was thus assumed to contain 5377, 4138 and 3060 "Home", "Work" and "Other" parking spaces, respectively. Some of the residential customers were summer houses, and they were assumed to be occupied only during the summer by one vehicle each. Consequently, the number of vehicles in the city increased by 333, one car per summer house, only during the summer weeks. In addition, the number of parking spaces in each state increased by 333 in summer. The authors assumed an EV penetration level of 100%, representing a future scenario, in order to study the most severe impact on the power grid by charging EVs.

A decision was made to proportionally distribute the number of parking spaces for both "Work" and "Other" states based on each customer's yearly electricity consumption compared with the total yearly electricity consumption of the category. For example, the "Work" parking spaces were distributed on the customers belonging to the "Work" state in proportion to their yearly electricity consumption. A higher electricity consumption indicates that more people are present at the workplace, which results in more EVs at the parking lot. In total there were 2.37 parking spaces per vehicle in the city. For comparison, in [34] the authors estimated that on average there are 2.2 parking spaces per vehicle in US cities.

Charging ports in this study were assumed to have a power of 3.7 kW, and were assigned to the same busbars as their corresponding customers. In case of the number of parking lots allocated to a busbar was not an integer, the number was approximated to the nearest integer. EV charging load – in every busbar – was treated as a balanced 3-phase load, regardless of the number of charging ports assigned to the busbar.

Vehicles were randomly assigned to parking lots that corresponded to the states they occupy at every time step t. Each vehicle, nonetheless, occupied the same parking space until a change in state occurred, i.e., EVs changed parking lots only when changing the parking state $X_t \neq X_{t-1}$ and then EVs occupied the new parking lot until the next change in state.

It was assumed, in [29], that EVs had sufficiently large batteries to satisfy their driving needs, possibly in the near future. Nowadays, adaptations are rarely needed when switching to EVs. For example, 95% of American drivers need to adapt only one week a year if they replace their car with one of the currently available EVs [35].

Instead of specifying a battery capacity for the EVs, the model measured the change in the battery charge compared with the beginning of the simulation. In other words, as EVs moved in the city, the change increased, and as EVs started charging the change decreased. If an EV charged an equal amount of energy to the energy consumed, then the change in battery charge would be zero. This means that the EV has the same charge state that it had in the beginning of the simulation. The change of battery charge E (kWh) for vehicle n at time t was defined as:

$$E_t^n = \begin{cases} E_{t-1}^n + 3.7 \times \Delta t & \text{if charging} \\ E_{t-1}^n - \eta \times D & \text{if driving} \\ E_{t-1}^n & \text{otherwise} \end{cases} \tag{6}$$

where η is the AC consumption rate (kWh/km), and D is the distance in (km) driven by the vehicle. η was assumed in this paper to be 0.25 kWh/km in winter and 0.15 kWh/km in summer, see [36, 37] for a detailed discussion of the impacts of the ambient temperature on η. The traveled distance D was randomly sampled from the travel survey between respective states. It was assumed to occur instantaneously when a change in state S occurred, similar to [38]. The charging load P (kW) of station ψ at time t was estimated to be:

$$P_t^{\psi} = 3.7 \times N_t^{\psi} \tag{7}$$

where N_t^{ψ} is the number of charging vehicles in station ψ at time t.

The authors did not simulate different spatio-temporal EV mobility patterns when simulating the different scenarios – described in Section 2.3. This was done to facilitate comparisons of the results of the PV penetration scenarios.

3 Results

This section contains the results of the power flow simulations with PV power and EV charging.

3.1 *Electricity consumption and generation*

The electricity consumption was in total 5.43 GWh during the two winter weeks and 1.82 GWh during the two summer weeks. The additional electricity consumption due to EV charging during the winter and summer weeks was 504 MWh in the winter and 311 MWh in the summer. This means that the electricity consumption increased by 9.3% in the winter and 17.1% in the summer due to EV charging. Every EV, in the EV model, drove approximately on average 27 km/day. In comparison, the average daily driving distance, during 2015–2016, in Sweden was 25 km/day [39].

The electricity consumption and PV power generation show a seasonal and daily variation, see Fig. 3 and Fig. 4. Whereas the load was

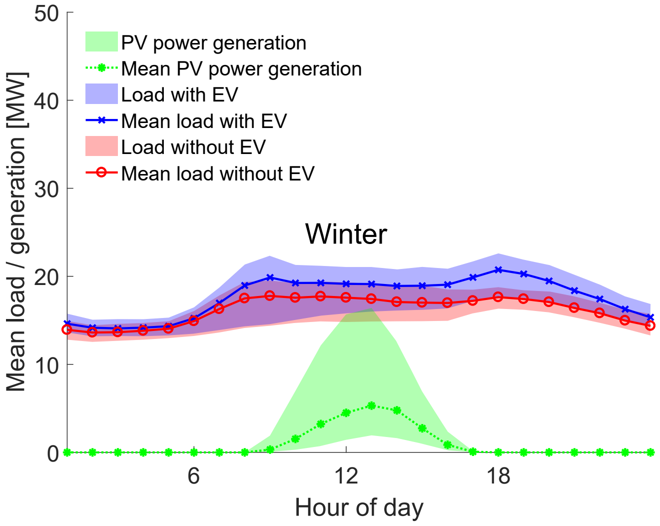

Fig. 3: Daily electric load with and without EV charging and average PV power generation in the two winter weeks. The yearly PV penetration is 50%.

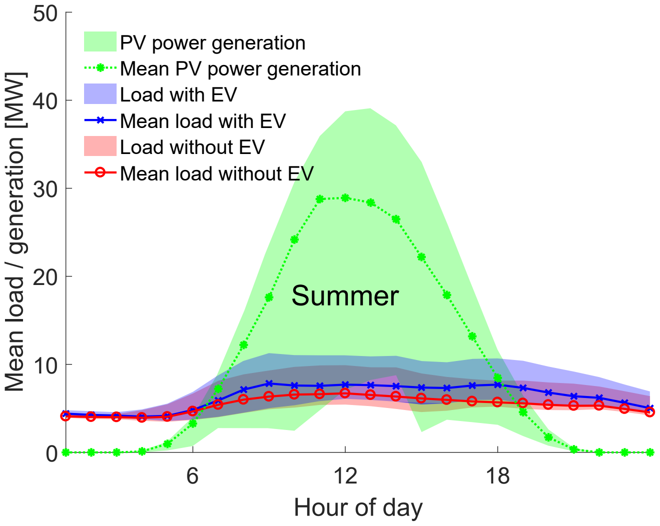

Fig. 4: Daily electric load with and without EV charging and average PV power generation in the two summer weeks. The yearly PV penetration is 50%.

more than twice as high in the winter compared to the summer, the PV power generation was five times higher in the summer than in the winter. The EV charging load during weekdays had two distinctive peaks at 9 and 18 both in the winter and in the summer. The EV charging load during weekends was highest in the afternoon. The differences in the maximum and minimum limits of the PV power generation in Fig. 3 and Fig. 4 were due to weather conditions, of which the cloudiness was of most significance. The lower limit of the PV power generation in Fig. 4 was due to low values on two days, one with an overcast sky in the morning and one with an overcast sky in the evening.

The daily total electricity consumption was on average 7% and 11% higher during weekdays than weekends in the winter without and with EV charging, respectively. In the summer, the daily electricity consumption was on average 14% and 22% higher during weekdays than weekends without and with EV charging, respectively.

Due to the northern latitude and varying cloudiness, the magnitude and the length of the PV power generation varied significantly over the seasons and days. In the winter, the PV power generation was negligible during the morning EV charging peak and zero during the afternoon EV charging peak.

A duration plot of the hourly net load, defined as total electric load minus total PV power, is shown in Fig. 5. The PV penetration was set to 50% on a yearly basis. During 46% of the hours in the summer, the total PV power generation exceeded the electric load without EV charging (negative values in Fig. 5). With EV charging, this share is reduced to 44%. In the winter, the hourly load always exceeded the generation. However, for individual nodes and LV grids, the generation exceeded the load even in the winter. This means that active power curtailment of the PV systems was still needed to avoid overvoltage in the winter. Note that all the four net load duration curves – winter with and without EV charging and summer with and without EV charging – are sorted individually. It is therefore not possible to compare the net load for each hour.

The share of houses with PV systems for different PV penetration levels is shown in Fig. 6. The number of PV systems is the same with or without EV charging, and in both the summer and the winter. The mean share of all 10 simulations per PV penetration level increased linearly with increased PV penetration. There was a difference between individual simulations, which depended on the average size of the PV systems that were chosen.

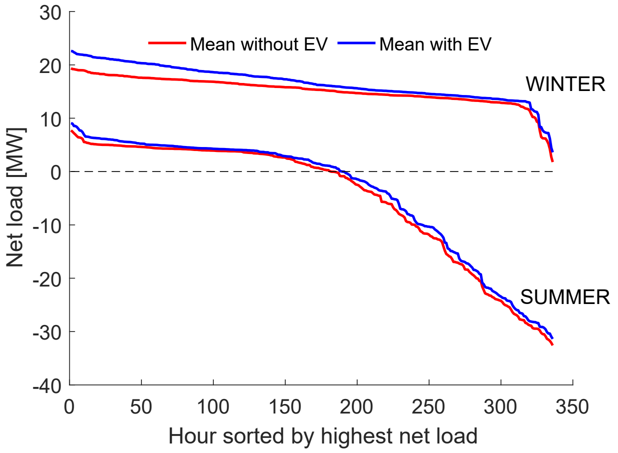

Fig. 5: Duration plot of the electric net load (load minus generation) with and without EV charging in the two winter weeks and the two summer weeks. The yearly PV penetration is 50%.

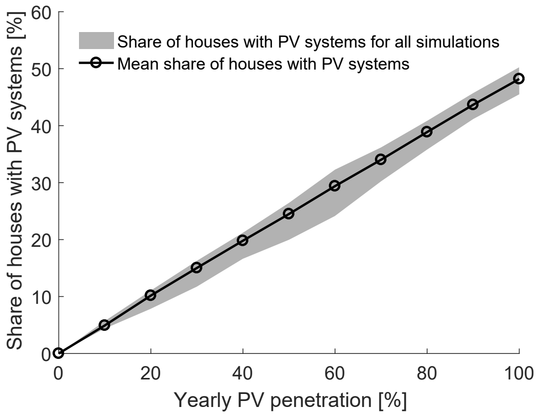

Fig. 6: Share of houses with PV systems for each PV penetration level. Mean values of and ranges for 10 simulations with different PV system dispersions per penetration level.

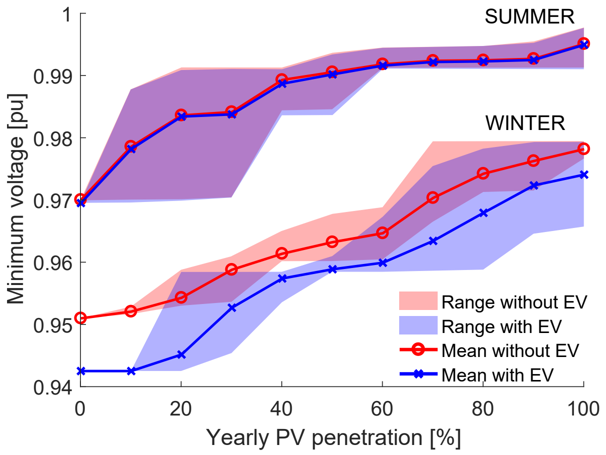

Fig. 7: Minimum voltage during the two summer weeks and two winter weeks with and without EV charging. The undervoltage limit is 0.90 pu. Mean values of and ranges for 10 simulations with different PV system dispersions per penetration level.

3.2 *Voltage extremes*

With the active power curtailment algorithm for the PV systems, the maximum voltage did not exceed 1.10 pu for any PV penetration level. The minimum voltage was never below the undervoltage limit of 0.90 pu, shown in Fig. 7. This was true even when EV charging was added. With EV charging, the minimum voltage in the winter decreased with approximately one percent.

The increase of the minimum voltage with increasing PV penetration level shows that the lowest voltage occurred during sunshine hours, and the affected node changed between simulations and for different PV penetration levels. The range of minimum voltage for each simulation run was wide for both summer and winter, and for both with and without EV charging.

The reduction in voltage when the EV charging was added was larger in the winter weeks than in the summer weeks. This indicates that on average more EVs were charged in or close to the grid node with the minimum voltage in the winter than in the summer. Furthermore, the power flow solution results in a non-linear relationship between the net load and the busbar voltages [27].

3.3 *PV power curtailment*

The share of all PV systems that had to be curtailed for at least one hour was on average 4 to 15 times higher in summer than in winter for every PV penetration level, as can be seen in Fig. 8. With an initial PV penetration of 100% on a yearly basis, active power curtailment was needed for, on average, 71% of the PV systems during the summer weeks. With EV charging, these shares were decreased by one to six percent, equal to less than one percentage point for each level. The relative reduction in the winter was up to 20% when EV charging was added, but the absolute numbers were still relatively low compared to the summer.

The relative reduction in the PV power generation in the summer and winter weeks due to active power curtailment is shown in Fig. 9. The reduction due to EV charging was minor, both in the summer and in the winter. The losses were always higher without EV charging than with EV charging for each selection of rooftops for PV systems (i.e., each simulation run). However, the range of the results for the simulations overlapped each other, indicating that the spatial distribution of the PV system has higher influence on the active power curtailment losses than the addition of EV charging.

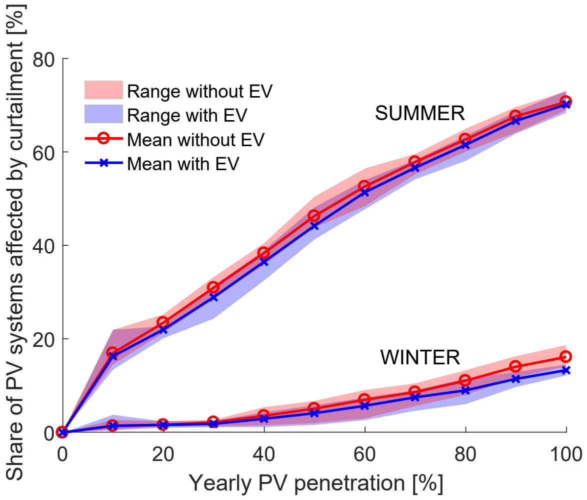

Fig. 8: Share of PV systems affected by curtailment losses in the winter and in the summer for scenarios with and without additional EV charging. Mean values of and ranges for 10 simulations with different PV system dispersions per penetration level.

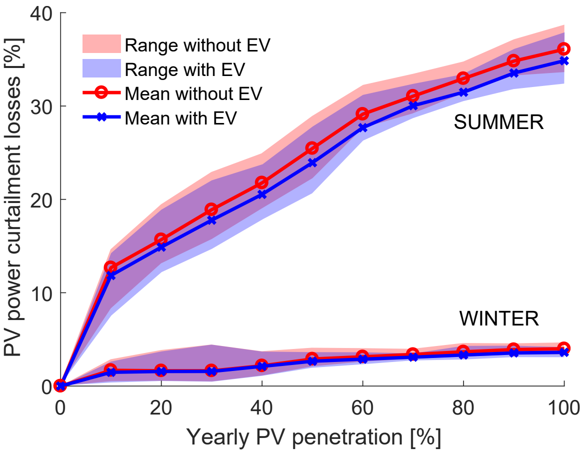

Fig. 9: PV power curtailment losses relative to the theoretical PV power generation. Mean values of and ranges for 10 simulations with different PV system dispersions per penetration level.

4 Discussion

This study indicates that EV charging, both public and at home, does not significantly reduce the need of active power curtailment of PV systems in the studied MV-LV distribution system. Since similar studies on large distribution systems consisting of both MV grids and several LV grids are lacking in the literature, it is difficult to compare the results to previous research.

Even though the EV charging power was much higher during the day than during the night, the often short period of very high PV power generation at noon could not be met by the additional EV charging load. Another important reason was the spatial distribution of the workplaces, residential and other buildings in relation to the travel habits of the EV owners. This might have led to a spatial mismatch between PV power generation and EV charging load. In a municipality with both urban and rural residential areas, voltage problems – if there are any – are likely to occur in rural areas. This is due to relatively weak electricity grids, long feeders and large aggregated roof areas available for PV installations, in combination with a low electricity use in the houses. The EVs are often driven from homes to work, and assumed to be charged at work during the day. Meanwhile the PV power generation in the residential areas is high during working hours. In the afternoon and evening the cars are driven from work to home, and the extra charging load in the evening coincides with lower or no PV power generation. Hence, the need of power curtailment of the PV systems might occur in residential areas during the day.

One way to lower the need for power curtailment and thus to increase the total PV power generation, is to use smart charging of the EVs. This could be, for example, scheduling of the charging of the EVs to periods with high PV electricity generation and low electricity demand. The battery capacity of an EV might be sufficient for charging only at work and not at home, depending on the driving patterns. In order to make scheduled charging an attractive option, pricing schemes with high intra-day price variability or extra revenues are most certainly needed. Neither of these are used in Sweden as of today. With low electricity price variability and no incentives, the majority of the EV owners will most probably charge their cars as soon as possible after driving.

5 Conclusion

The findings of this paper are that (i) a fully electrified car fleet within the studied distribution system area increased the electricity consumption with 9.3% and 17.1% during the two winter weeks and two summer weeks, respectively, (ii) on average 71% of the PV systems were curtailed in the summer with a 100% PV penetration on a yearly basis, (iii) opportunistic EV charging can only marginally lower the active power curtailment losses, and (iv) the minimum voltage is reduced more by EV charging in the winter than in the summer but stays above the undervoltage limit.

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6 References

1 Masson, G., Kaizuka, I.: 'Snapshot of Global Photovoltaic Market (1992-2017)',Technical report No. 33:2018, (IEA-PVPS, 2017), pp. 1-15

2 Bollen, M.H., Hassan, F.: 'Integration of Distributed Generation in the Power System' (John Wiley & Sons, New Jersey, 1st edn, 2011)

3 Tran, M., Banister, D., Bishop, J.D.K., McCulloch, M.D.: 'Realizing the electric-vehicle revolution', Nat. Clim. Change, 2012, 2, (5), pp. 328–333

4 Deilami, S., Masoum, A.S., Moses, P.S., Masoum, M.A.S.: 'Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile', IEEE Trans. Smart Grid, 2011, 2, (3), pp.456–467

5 Rathnayaka, A.J.D., Potdar, V.M., Dillon, T., Hussain, O., Kuruppu, S.: 'Analysis of energy behaviour profiles of prosumers', IEEE 10th Int. Conf. on Industrial Informatics, Beijing, China, Jul 2012, pp. 236–241

6 Steffel, S.J., Caroselli, P.R., Dinkel, A.M., Liu, J.Q., Sackey, R.N., Vadhar, N.R.: 'Integrating Solar Generation on the Electric Distribution Grid', IEEE Trans. Smart Grid, 2012, 3, (2), pp. 878–886

7 von Appen, J., Braun, M., Stetz, T., Diwold, K., Geibel, D.: 'Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid', IEEE Power Energy M., Mar 2013, 11, (2), pp. 55–64

8 Braun, M., Stetz, T., Bründlinger, R., *et al.*: 'Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects', Prog. Photovoltaics, 2012, 20, (6), pp. 681–697

9 Babacan, O., Torre, W., Kleissl, J.: 'Siting and sizing of distributed energy storage to mitigate voltage impact by solar PV in distribution systems', Sol. Energy, 2017, 146, pp. 199–208

10 Hashemi, S., Østergaard, J., Yang, G.: 'A Scenario-Based Approach for Energy Storage Capacity Determination in LV Grids With High PV Penetration', IEEE Trans. Smart Grid, 2014, 5, (3), pp.1514–1522

11 Pompodakis, E.E., Drougakis, I.A., Lelis, I.S., Alexiadis, M.C.: 'Photovoltaic systems in low-voltage networks and overvoltage correction with reactive power control', IET Renew. Power Gener., 2016, 10, (3), pp. 410–417

12 Tonkoski, R., Lopes, L.A.C.: 'Impact of active power curtailment on overvoltage prevention and energy production of PV inverters connected to low voltage residential feeders', Renew. Energ., 2011, 36, (12), pp. 3566–3574

13 Stetz, T., Diwold, K., Kraiczy, M., Geibel, D., Schmidt, S., Braun, M.: 'Techno-economic assessment of voltage control strategies in low voltage grids', IEEE Trans. Smart Grid, 2014, 5, (4), pp. 2125–2132

14 Malik, O., Havel, P.: 'Active Demand-Side Management System to Facilitate Integration of RES in Low-Voltage Distribution Networks', IEEE Trans. Sustain. Energy, 2014, 5, (2), pp. 673–681

15 Hashemi, S., Østergaard, J.: 'Methods and strategies for overvoltage prevention in low voltage distribution systems with PV', IET Renew. Power Gener., 2017, 11, (2), pp. 205–214

16 Swedish Standards Institute: 'SS-EN 50160 - Voltage characteristics of electricity supplied by public distribution systems', 2011.

17 Dallmer-Zerbe, K., Stillahn, T., Erge, T., Wille-Haussmann, B., Wittwer, C.: 'Analysis of the Exploitation of EV Fast Charging to Prevent Extensive Grid Investments in Suburban Areas', Energy Technol., 2014, 2, (1), pp. 54–63

18 van der Burgt, J., Vera, S.P., Wille-Haussmann, B., Andersen, A.N., Tambjerg, L.H.: 'Grid impact of charging electric vehicles; study cases in Denmark, Germany and The Netherlands', 2015 IEEE Eindhoven PowerTech, Eindhoven, Netherlands, Sep 2015, pp. 1–6

19 Lim, K.Y., Lim, Y.S., Wong, J., Chua, K.H.: 'Distributed Energy Storage with Real and Reactive Power Controller for Power Quality Issues Caused by Renewable Energy and Electric Vehicles', J. Energ. Eng., 2016, 142, (4)

20 Luthander, R., Lingfors, D., Widén, J.: 'Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage', Sol. Energy, 2017, 155, pp. 1319–1325

21 Luthander, R., Shepero, M., Munkhammar, J., Widén, J.: 'Photovoltaics and opportunistic electric vehicle charging charging in a Swedish distribution grid', 7th International Workshop on Integration of Solar into Power Systems, Berlin, Germany, Oct 2017

22 Bollen, M.H., Beyer, Y., Styvaktakis, E., Trhulj, J., Vailati, R., Friedl, W.: 'A European benchmarking of voltage quality regulation', 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Stockholm, Sweden, June 2013

23 Swedish Meteorological and Hydrological Institute (SMHI): 'STRÅNG - a mesoscale model for solar radiation', http://strang.smhi.se, accessed Sep 2015

24 Lingfors, D.: 'Solar Variability Assessment in the Built Environment: Model Development and Application to Grid Integration'. PhD thesis, Uppsala University, 2017

25 ESRI: 'ArcGIS Desktop', http://desktop.arcgis.com/en, accessed Sep 2015

26 Duffie, J.A., Beckman, W.A., Worek, W.M.: 'Solar Engineering of Thermal Processes' (John Wiley and Sons Ltd, New York, 1980, 2 edn. 1994)

27 Saadat, H.: 'Power System Analysis' (PSA Publishing, 1998, 3rd edition, 2010)

28 Widén, J., Wäckelgård, E., Paatero, J., Lund, P.: 'Impacts of different data averaging times on statistical analysis of distributed domestic photovoltaic systems', Sol. Energy, 2010, 84, (3), pp. 492–500

29 Shepero, M., Munkhammar, J.: 'Modelling charging of electric vehicles using mixture of user behaviours', 1st E-mobility Power System Integration Symposium, Berlin, Germany, Oct 2017

30 Koralov, L.B., Sinai, Y.G.: 'Theory of Probability and Random Processes' (Springer-Verlag Berlin Heidelberg, 2007, 2nd edn. 2012)

31 Grahn, P., Alvehag, K., Soder, L.: 'PHEV utilization model considering type-of-trip and recharging flexibility', IEEE Trans. Smart Grid, 2014, 5, (1), pp. 139–148

32 SIKA: 'RES 2005 – 2006 The National Travel Survey', Technical Report No. 2007:19, 2007

33 Statistiska centralbyrån: 'Vehicles in counties and municipalities', Technical Report Statistik 2017:3, 2017

34 Davis, A.Y., Pijanowski, B.C., Robinson, K., Engel,B.: 'The environmental and economic costs of sprawling parking lots in the United States', Land Use Policy, 2010, 27, (2), pp. 255–261

35 Pearre, N.S., Kempton, W., Guensler, R.L., Elango, V.V.: 'Electric vehicles: How much range is required for a day's driving?', Transportation Research Part C: Emerging Technologies, 2011, 19, (6), pp. 1171–1184.

36 Salisbury, S.: 'Cold weather on-road testing of a 2015 Nissan Leaf', Idaho national laboratory, Technical Report No. NL/EXT–16–39028, 2016.

37 Besseling, I.J.M., Hereijgers, J.A.J., van Oorschot, P.F., Nijmeijer, H.: 'Evaluation of 20000 km driven with a battery electric vehicle', In Proceedings of the European Battery, Hybrid and Fuel Cell Electric Vehicle Congress, Brussels, Belgium, Oct 2011, pp. 1–10.

38 Rolink, J., Rehtanz, C.: 'Estimation of the availability of grid-connected electric vehicles by non-homogeneous semi-Markov processes', 2011 IEEE PES Trondheim PowerTech Power Technology, Trondheim, Norway, Sep 2011, pp. 1–7.

39 Trafikanalys: 'RVU Sverige - den nationella resvaneundersökningen 2015–2016', Technical Report Statistik 2017:13, 2017.