Impact of Different Charging Strategies for Electric Vehicles on their Grid Integration

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Abstract

The necessary extensive expansion of the electricity grid infrastructure is not only a technical challenge, its planning and realization additionally leads to far-reaching economic and socio-political challenges. In the context of the current FfE project Merit Order Grid-Expansion 2030 (MONA 2030) an integral comparison of grid optimization measures to integrate the increasing amount of volatile renewable electricity and new loads (e.g. electric vehicles (EV)) in the distribution grids is carried out.

Therefor the FfE simulation model GridSim, a tool for detailed 3-phase calculations of potential distribution grids with high market penetration of decentralized generation, electric vehicles, heat pumps or energy storage systems was developed. GridSim empowers the user to perform simulations, based on load flow calculations, and to analyze and evaluate critical operating conditions like the exceedance of voltage tolerance ranges or component overloads as well as the effects of grid-optimizing measures like adjustable distribution grid transformers or like in this case different charging strategies of EV.

Based on the survey results of “Mobilität in Deutschland 2008” (Mobility in Germany 2008) a methodology was derived to generate realistic driving profiles for electric vehicles. This model calculates the electrical energy demand and in addition the times when the EV is not in use. Furthermore it categorizes where the EV is parked, which makes it possible to evaluate if the EV is parked at home. In the presented paper EV only are charged at home. In total more than 10.000 different driving profiles were generated and used in the simulation model GridSim.

In GridSim different charging strategies like uncontrolled charging after plug in, optimized self-consumption of PV-energy or tariff-oriented strategies are implemented, which can be analyzed according to their effects on the distribution grids.

To sum up, this paper gives an overview of different charging strategies for EV and their impact on distribution grids. It is shown that a price oriented charging strategy leads to high charging concurrency and hence is the most critical one regarding the grid integration. By optimizing the own consumption with an electric vehicle the negative impact on the grid can be slightly reduced.

1 Introduction

One of the main goals of the energy transition is the decarbonization of the energy system to limit the temperature rise to 2 °K. This means that we have to reduce greenhouse gas emissions until 2050 by 80 – 95 % compared to 1990 [1]. Therefor it. One key element to reach this target is the goal to increase the energy production by renewable energies like photovoltaic and wind.

Especially photovoltaic systems are installed mostly in the distribution grids, which leads to new challenges since the direction of load flows changes and these grids are sometimes not designed to transport these amounts of power. In addition it is necessary to use renewable energies also for heating and mobility. To speed up the electrification of vehicles, the federal government of Germany decided to support the installation of charging stations for electric vehicles (EV) to reach the goal of one million EV in 2020 and six million EV in 2030. Most of the time these EV will be charged at home which leads to new loads with high power in the distribution grids.

Within the project MONA 2030[1] a comparison of measures and technologies for grid optimization is currently carried out. The goal of this project is to derive a ranking like a merit order for all relevant grid-optimizing measures (gom) and technologies. In this project also different charging control strategies for EV are simulated and evaluated.

2 Driving Profiles

The utilization of an EV has a determining influence on its charging process. Thus it is important to use reasonable driving profiles. Within the context of the study “Mobilität in Deutschland 2008” [2] representative day driving profiles were collected. In the projects MONA 2030 [3] and MOS 2030 [4] these day driving profiles were extended to year driving profiles as described below and used in this study.

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[1] The project MONA 2030 (funding code 03ET4015) is co-funded by the German Federal Ministry of Economic Affairs and Energy through the funding initiative “Zukünftige Stromnetze”. 16 project partners from the energy (e. g. system operators) and automotive industry support the research project through the provision of data and individual practical experience. The research is carried out by the “Forschungsstelle für Energiewirtschaft e.V.” (short: FfE English: Research Center for Energy Economics) in cooperation with the industrial partners. Further information of the project are provided at http://www.ffe.de/en_mona

To differentiate the participants of the mobility study [2] into different user groups (UG) with similar driving behaviour, additional information of the households, individuals as well as information about the routes were used in the project MOS 2030.

In a first step week driving profiles for commuters and non-commuters are created. A commuter week profile is assembled of seven different day driving profiles. The profile for Monday is chosen out of all Monday day driving profiles of a UG and CG. For the profiles from Tuesday to Friday day driving profiles of the corresponding days and the same CG as the Monday profile are chosen. To model a corresponding weekend behaviour driving profile of a Saturday and a Sunday are picked out of the same UG as used for the Monday profile. **Figure 1** illustrates an assembly of a commuter week driving profile.

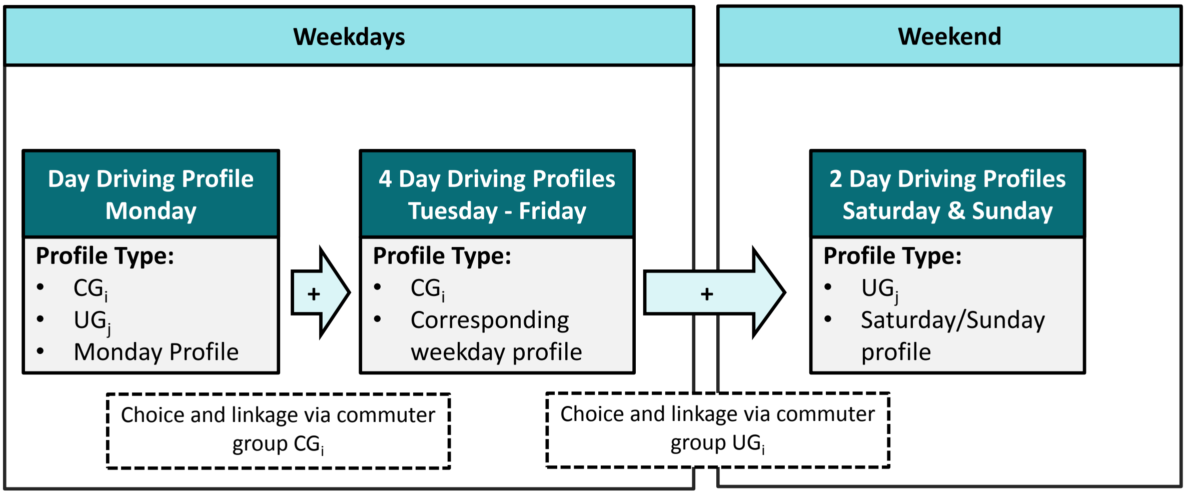

Figure 1: *Assembly of a commuter week driving profile*

To create a non-commuter week driving profile for each day of the week a day driving profile of the corresponding day is picked out of the same UG.

Considering holidays and bridge days these profiles are extrapolated in a second step to year driving profiles. A consumption model used in MOS 2030 determines the specific EV consumption taking the distinction of small cars, mid-range cars and top-of-the-range cars as well as the average velocity and the ambient temperature into account.

3 GridSim – the FfE Distribution Grid Model

The simulation model GridSim, which is developed by the FfE, is a modular simulation tool for detailed 3-phase calculations of low-voltage distribution grids. The focus is on the evaluation of future challenges and options for low-voltage distribution grids in the light of the energy transition and increasing distribution of new energy technologies. GridSim is able to analyze the backlashes of such new technologies like distributed power resources, battery storage systems as well as high market penetration of heat pumps, PV-systems and electrical vehicles. Critical grid conditions like exceeding of voltage tolerance ranges or component overloads can be identified and evaluated.

Before the start of the simulation, the electrical grid topology is determined and the properties of corresponding grid components like transformers are selected. One building is connected to each connecting node of the low voltage distribution grid. Depending on the chosen settlement model [5], one building can contain one or several housing units. For each housing unit, a 3-phase load profile as well as a heat demand profile is allocated. Optional, electrical vehicles can be assigned to each housing unit, however maximal one vehicle per unit. For each building, components like PV-systems, heat pumps or battery storage systems can be allocated. GridSim is also able to consider regional characteristics, by the implementation of the FfE regional model *FREM* [6], which provides regional high resolution data for various technical and economic aspects of the energy sector. The components are distributed randomly according to certain criteria among all buildings respectively housing units and are connected to corresponding load profiles (demand and supply) as well as driving profiles.

In the next step, detailed simulations of the modeled residential district are carried out. The residual load is calculated for each time step and each building, taking into account the electrical control of each individual component. The results are summarized in a residual load matrix. Subsequently, the current grid state is determined based on the residual load matrix and a load flow calculation. Thereby, all voltages, currents and component overloads are calculated for all positions inside the analyzed grid. As a result, the most likely positions for critical grid conditions can be identified. By this it can be determined, from which conditions on, grid-optimizing measures should be applied.

Next to the grid conditions, all load profiles and – for energy storage devices – State of Charges (SoC) for all components are calculated and saved. Based on this data, several aspects can be compiled subsequent to the load flow calculations. This includes energy balances for the entire grid area or equivalent full cycles of batteries. Furthermore, the impact of the chosen charge control strategies can be analyzed by the calculation of typical charge profiles. By generating CO_2 balances for the grid area environmental aspects can be considered.

4 Charging Control Strategies

Before the different charging control strategies are introduced some basic demands for the charging processes are explained. To design a practical useful charging control some general conditions which all charging control should meet are set. In respect of the SoC these conditions divide the battery in three fundamental sections *A*, *B* and *C* as shown in **Figure 2**.

To afford the owner of the EV a high flexibility a minimum SoC (SoC_{min}) is defined. Additionally the owner of the electric vehicle is able to schedule the next departure and define a SoC which the battery should reach until the departure ($SoC_{Departure}$).

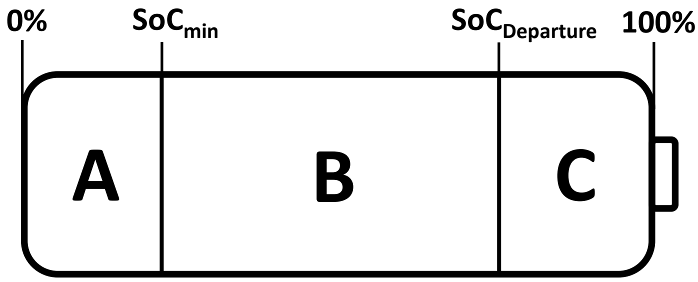

Figure 2: *The battery of an electric vehicle can be divided into three fundamental sections in respect of its State-of-Charge*

If an EV is connected to the charging station and the SoC is within section *A*, each of the regarded controls charges the battery up to the SoC_{min} as fast as possible.

Once the battery reached section *B* the charging process follows the strategy of the chosen control as long as it can be ensured that there is enough time to reach the $SoC_{Departure}$ within the remaining time until a scheduled departure. In case that there is not enough time to charge the battery to $SoC_{Departure}$ the EV is charged with the highest permissible charging power in order to get as close as possible to the demanded SoC.

After reaching section *C* the charging control follows the chosen strategy as described in the next sections.

4.1 Uncontrolled Charging

Uncontrolled charging is the most basic option to charge an EV. As soon as the EV is connected to the charging station it charges with the highest permissible charging power until the battery is fully charged or the vehicle is disconnected. This approach charges the battery with the maximum charging power regardless of the current SoC. Thus the conditions of charging to the SoC_{min} immediately and trying to reach the $SoC_{Departure}$ by the time of departure are met automatically.

4.2 Own Consumption Optimized Control

If a photovoltaic system is installed it is possible to charge the EV with an own consumption optimized control. The EV uses exclusively surplus power of the photovoltaic system to charge. Merely if the SoC_{min} or $SoC_{Departure}$ has to be reached while no surplus power is available the power is purchased from the grid.

4.3 Voltage Guided Control

The voltage guided strategy controls the charging power according to the voltage of the household junction. The charging power is defined by a function of voltage as shown in **Figure 3.**

P_{max} is the highest and P_{min} the lowest permissible charging power in respect of the power electronics. As long as the voltage of the household junction does not drop below $U_{critical,decrease}$ the EV charges with P_{max}. Otherwise the charging control reduces the charging power linearly in order to reduce the load and thus raise the voltage again. A voltage drop under U_{min} interrupts the charging process completely. In this study U_{min} *was set to 0.9 pu and* $U_{critical,decrease}$ *to 0.93 pu.*

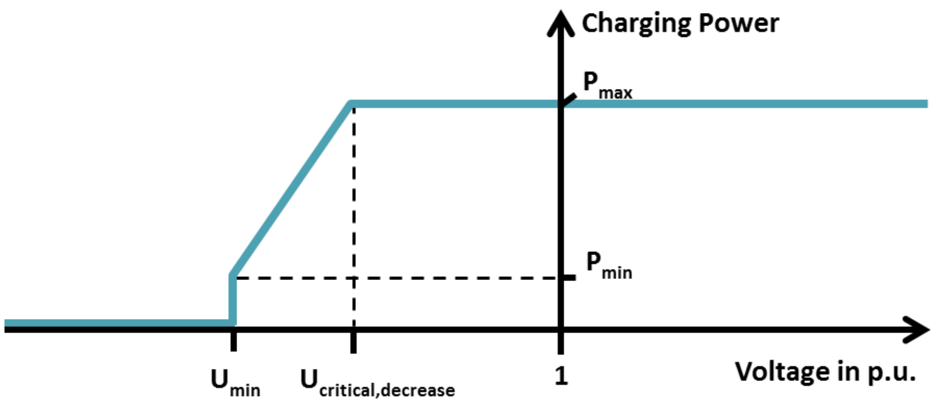

Figure 3: *Permissible charging power for voltage guided control*

4.4 Price Oriented Control

Another option is to charge the EV only if the price for the purchased energy is low. If the SoC of the EV is in status B the control picks out the cheapest time slots to charge the car up to the $SoC_{Departure}$ until the EV gets unplugged. In addition to that the EV can be charged with the following strategy. Therefore it is necessary to define a price threshold so that the charging control is able to decide if the EV should charge or not. Based on the assumption that an EV is charged almost every day the threshold is chosen as the mean price of the day. So basically the EV only charges if the current price falls below a defined price threshold which is lower than the daily mean.

Figure 4 illustrates the complete characteristic of the charging power as a function of the deviation from the mean price of the day. As soon as the price falls below $Price_{start}$ the EV charges with the maximum charging power $P_{Charge,max}$. The parameter $Price_{start}$ can be defined for every simulation in GridSim and was set to 0.3 which means that the charing process starts if the price is below 30 % of the mean price.

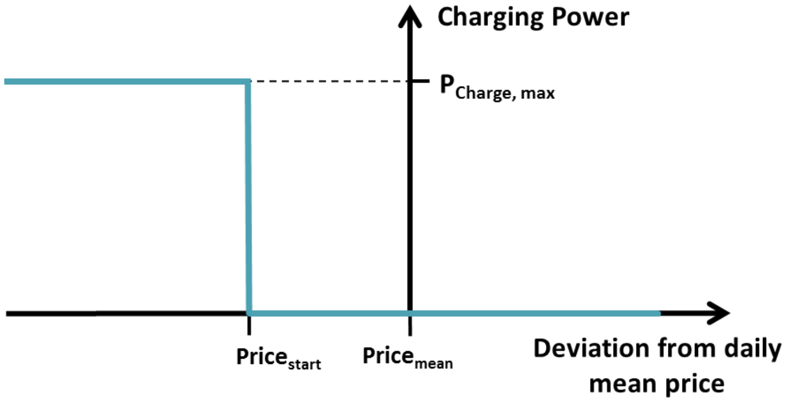

Figure 4: *The charging power depends on the deviation from the daily mean price*

5 Impact of different Charging Control Strategies

In this study the effects of different charging control strategies were investigated using the MONA-type grid 4, which is shown in **Figure 5**. This grid represents a rural area with 45 buildings including one household each. The grid consists of six strings with an average distance of 39 m between the grid connection points. The implemented transformer has a rated power of 630 kW.

The parameter sets of the simulations are based on scenario five in the MONA project, which is described in [7], [8]. For a better understanding

Table 1 shows the most important parameters regarding the penetration with additional components.

Table 1: *Penetration of the distribution grid with additional components*

Parameter	Penetration	Number of Elements
PV-plants	58 %	26
home storage systems	33 %	15
heat pumps	22 %	10
electric vehicles	50 %	23

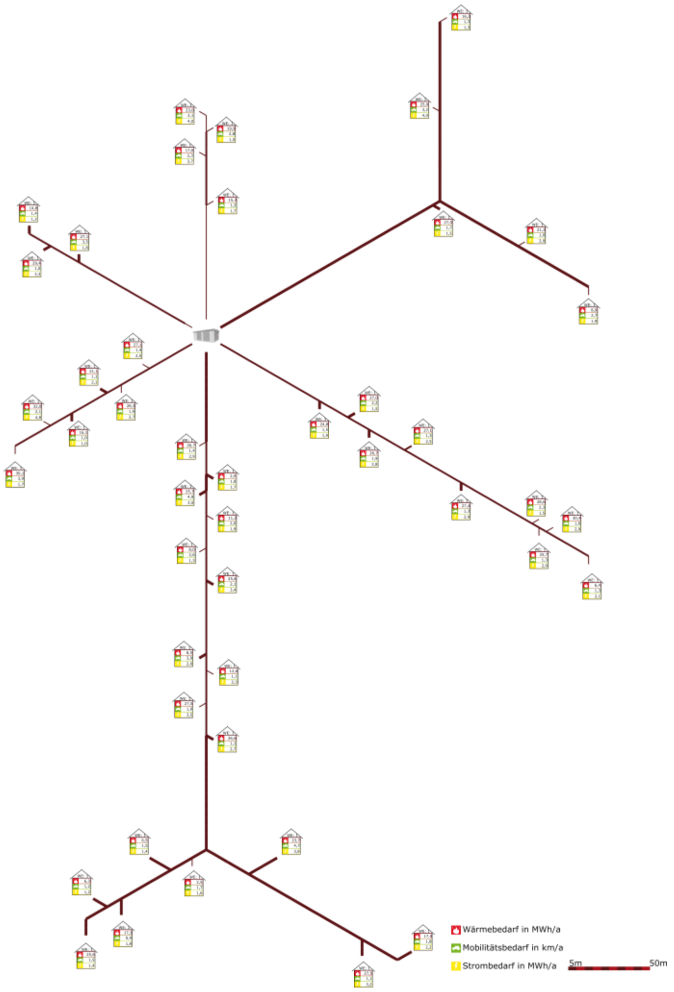

Figure 5: *Type grid 4 represents a typical rural grid with 45 buildings which consist of one household each.*

In addition **Table 2** gives an overview of the simulation parameters regarding the electric vehicles. It describes the share of battery and plug-in electric vehicles (BEV/PHEV) and which percentage of the EV gets charged at a wallbox.

Table 2: *Simulation input parameter regarding the electric vehicles*

Parameter	value	Unit
Share of BEV/PHEV	30 / 70	%
Battery Capacity BEV/PHEV	47 / 19	kWh
Charging power (1-phase)	3,3	kW
Charging power (3-phase; wallbox)	11	kW
Share of wallbox	50	%
SoC_{min}	12	%
$SoC_{Departure}$	70	%

5.1 Concurrency of the charging events

This part describes the impact on the concurrency of the charging events depending on the different charging strategies. **Figure 6** shows the maximum concurrency per weekday and daytime. The subplot top left respresents the uncontrolled charging which is almost the same than the voltage guided control (top right). The maximum concurrency is around six pm and has an value of 30 % which means, that 30 % of all EV in the evaluated grid are charged at this time. In addition it can be seen that the concurrency is lower on Fridays and at the weekend since the commuters come back earlier or stay at home at weekends often.

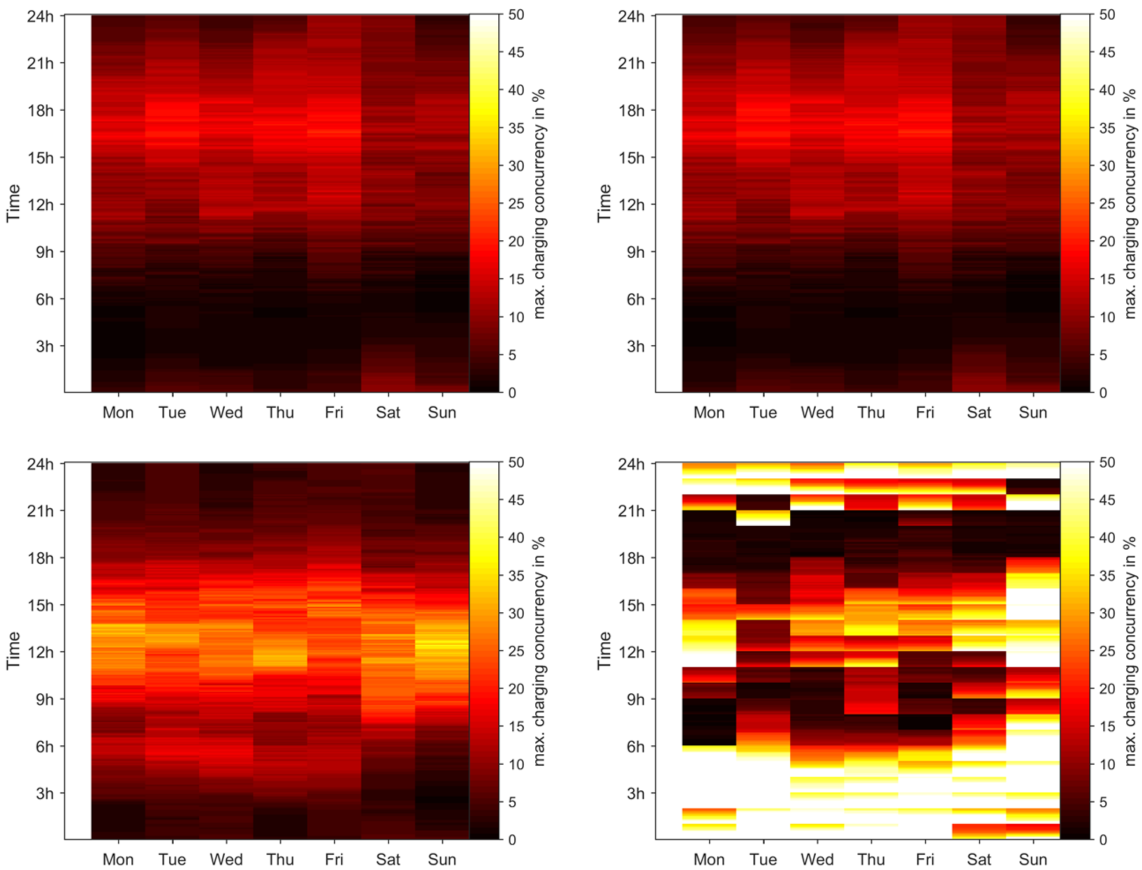

Figure 6: *Concurrency of charging events in dependency of the charging strategy (top left to bottom right: uncontrolled charging; voltage guided control; own consumption optimized control; price oriented control.*

Looking at the subplot bottom left, own consumption optimized control, the charging events are shifted to the times with high PV-power. The maximum concurrency (45 %) for this charge strategy is on Sunday at noon since many EV are connected to the grid at this time. Furthermore the charging concurrency in the early morning is higher with this charging strategy since many EV need to be charged before departure if there was not enough PV energy in the evening. The subplot bottom right shows that the concurrency for price oriented charging looks really different to the others. It has high concurrencies at different times, mostly in the early morning hours but also at other times. This is caused by the fact that the market prices for electricity vary over the year with most of the low prices during the nights. The maximum concurrency for this strategy is 94 %.

5.2 Power flows in the distribution grid

The different charging strategies affect the power flow in the low voltage grid as well. In **Figure 7** the power duration curve for each charging control strategy is shown. In this figure positive power represents power that was delivered from the middle voltage grid to the low voltage grid (demand). Negative power implicates that energy was feed into the medium voltage grid, which means that there was more production from PV-plants than demand at this time.

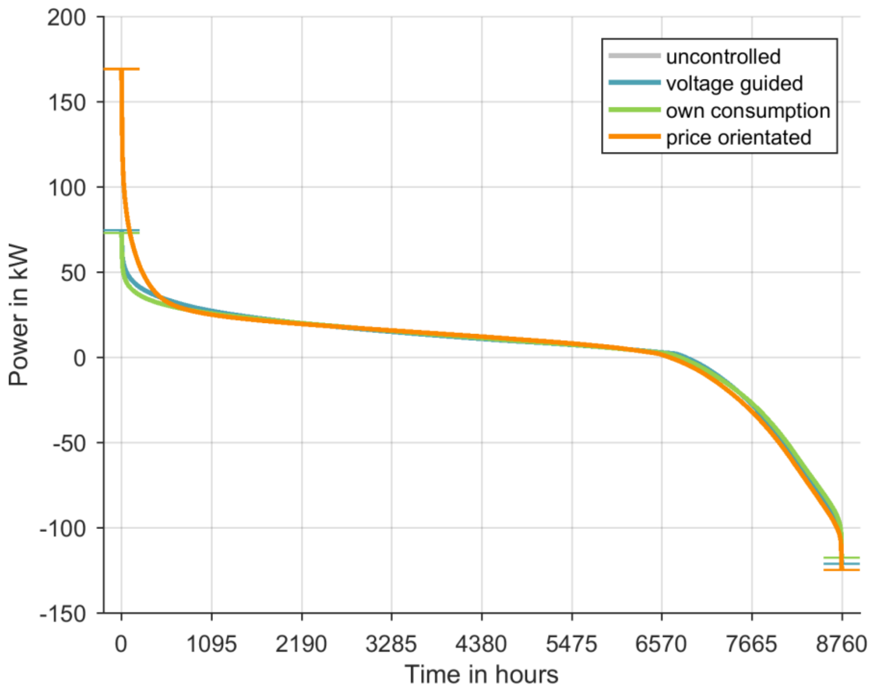

Figure 7: *Power duration curve of the transformer for the different charging control strategies*

The different charging control strategies mainly affect the peak power (left part of the curve). In these 500 hours with the highest load the price oriented control leads to a peak power of 170 kW, which is more than double the power of the uncontrolled charging strategy (75 kW). These values correspond to the charging concurrency which is highest for the price oriented control. In contrast the own consumption optimized control reduces the peak power slightly, since the maximum charging concurrency is not in the evening hours with the highest load but during the day. At most of the time (middle part of the curve) the charging controls have no influence on the power duration curve. Furthermore the own consumption optimized control reduces the maximum negative power the most, which can be seen at the right side of the curve.

In total none of the charging control strategies leads to critical power flows over the transformer which has a rated power of 630 kVA and additional there was no overload on any line detected during the simulations.

5.3 Voltage Reserve

The second parameter which describes the status of an electricity grid is voltage. In Germany the voltage must be within a ±10 % band of the rated voltage [9] at each grid connection point. In **Figure 8** the duration curve of the voltage reserve for all charging control strategies and for different charging power of the wallboxes (11 kW and 22 kW) is shown. The voltage reserve is defined as the minimum distance to either the upper or the lower voltage border, e. g. if the measured voltage is 1,02 pu the distance to the upper border is 8 % and to the lower border is 12 % and therefore the voltage reserve is 8 %. A negative value of the voltage reserve means that the voltage is outside the allowed bandwidth.

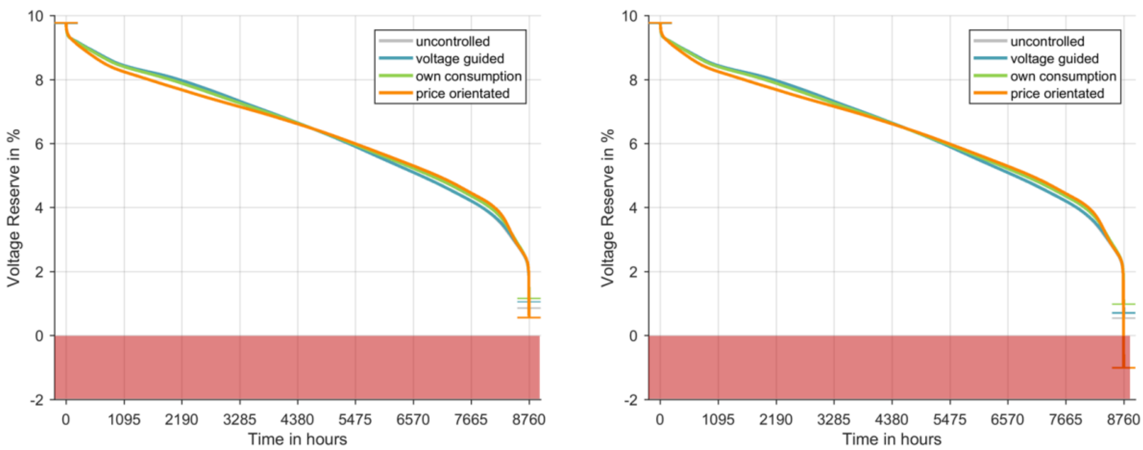

Figure 8: *Duration curve of the voltage reserve of the different charging control strategies; left side: maximum charging power 11 kW, right side: 22 kW*

The left figure above shows that with a maximum charging power of 11 kW there is no exceedance of the voltage band. The lowest voltage reserve occurs for the price oriented charging strategy which also results in the highest loads, which was shown in 5.2. In contrast to that this charging strategy leads to voltages which are outside the allowed range if the charging power of all wallboxes is set to 22 kW. The most critical charging strategy regarding the voltage is the price oriented control which has a negative influence on the voltage in the grid compared to the uncontrolled charging. The voltage guided and the own consumption optimized charging strategy improve the voltage quality and therefore help to integrate more EV into the power systems.

6 Conclusion

This comparison of different charging control strategies points out their impact on the electricity grid. It is shown that the voltage guided control which only reduces the charging power in times critical times is advantageous for the grid integration compared to the uncontrolled charging. Furthermore this study shows that in the described grid and scenario the own consumption optimized control is the best control strategy. In contrast the price oriented strategy leads to high charging concurrency during the night and thus to the most critical grid conditions.

7 References

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