Optimal De-Centralized Smart Home-Charging: Potential Study

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***Abstract*—This paper evaluates the impacts of electric vehicles' (EVs') smart charging algorithms on reducing the peak of the total load of households. Two smart charging schemes are proposed. The first scheme—postponed charging—is defined as reducing the charging power if the total load exceeds the fuse size, thereby sometimes postponing the charging. The second scheme—capacity-filling charging—is defined as charging the EVs with the difference between the fuse size and the house load, i.e., the available capacity. Both schemes were benchmarked to the uncontrolled charging scheme.**

The study was evaluated on 10 different Swedish simulated detached houses without electric heating, and using various combinations of charging powers and fuse limits. The results show that the worst house—the house that needed smart charging the most—needed postponed charging 8 days a year to avoid breaking the fuse. Moreover, postponed charging increased the charging duration, and thus inconvenience to the EV owners, by at most 4 hours. On the other hand, the capacity-filling charging scheme could increase or decrease the charging duration—compared to the uncontrolled charging. An increase is expected if the difference between the fuse size and the house load is smaller than the uncontrolled charging power. The charging duration will be shorter if the difference between the fuse size and the house load is larger than the comparable uncontrolled charging power.

The capacity-filling scheme proved to be more convenient, as it did not increase the charging duration by more than 3 minutes. Moreover, it reduced the charging duration for at least 198 days a year.

The results indicate that charging the EVs by the available capacity—the difference between fuse size and house load—is recommended compared to constraining the charging power.

I. Introduction

The number of plug-in electric vehicles (EVs) in the world increases rapidly and is expected to rise globally in coming years [1]. These EVs need to be charged via a charging infrastructure that can handle an intermittent high power demand at a multitude of locations in the electricity grid [2], often at the end-user, such as e.g. for home-charging. Attempts to design controlled charging algorithms have been made, with optimization schemes for a variety of purposes including reducing grid impact and optimizing the use of locally generated power [3], [4].

Generally, this so-called smart charging can be defined as a demand-side management strategy for controlling the charging of an EV for technical or economic benefits [4]. Recent research has shown that controlled charging can improve grid voltage [5], [6], grid components loadings [6]–[8], grid losses [5], peak load [9], charging costs [10], valley filling [11], and renewable energy source (RES) integration [12].

A challenge for introducing smart charging is to design algorithms that can be applied directly to existing systems [4], and therefore it has to be accepted among EV owners, charging station owners and grid operators, who are the essential stakeholders in this case. For the case where neither the charging station owner nor the grid operator are affected in terms of altered operation, there is a potential to improve the charging for the EV owner (who may or may not be the charging station owner). Arguably, from EV owner's perspective, the charging time should be minimized, in which case the smart charging schemes need to maximally utilize the local power system, while keeping it within operational limits.

Furthermore, by adopting a de-centralized charging scheme, which minimizes the need for information transfer compared with a centralized charging scheme [4], it is possible to enhance security and maximize privacy for each stakeholder.

This paper first investigates the necessity for smart home-charging in scenarios of various fuse levels. Second, it presents two types of de-centralized smart home-charging algorithms that focus on minimizing the electric vehicle charging-time based on capacity-filling the load to within household fuse limits and EV charger limits based on only household load level as information. These results are then compared with results from modelling conventional uncontrolled-type of home-charging.

II. Methods

A. Residential load

The residential load, household electricity load patterns, were generated based on the Widén model in order to obtain minute resolution electricity use profiles [13], [14]. This model is a Markov-chain model based on generating synthetic occupant activity patterns and consequent electricity use. It was trained on Swedish electricity use patterns and set to simulate a detached house without electric heating with 2 adult inhabitants per household to be close to the average of 2.5 inhabitants per household in Sweden [15]. In total ten households over one year were simulated for this study.

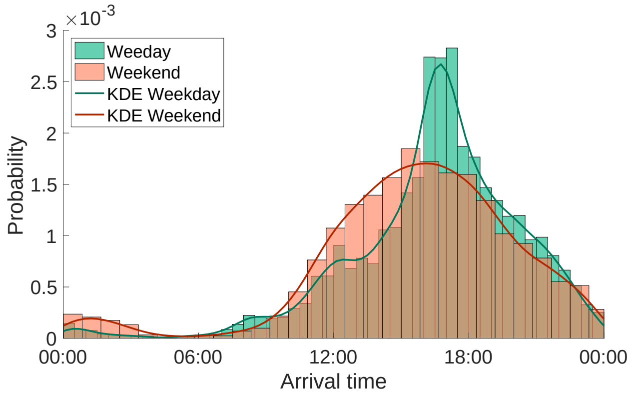

Fig. 1. A histogram of the arrival time of survey trips ending at home for both weekdays and weekends [16]. A kernel density estimate (KDE) is also presented in the figure.

B. EV daily charging demands

A Monte Carlo model is used to estimate the daily energy requirement of EVs. The daily energy requirement is used then to estimate the potentials of smart charging.

The model uses the mobility data provided in the Swedish travel survey [16] to estimate the charging demand of EVs. The travel survey included the arrival/departure times of trips made by cars and the distance traveled in these trips. In addition, the origin and destination locations of these trips were recorded.

The model takes as input, the time of home-arrival of an EV and the distance traveled during the day. The model assumes that the EV will only charge once during the day, and that this charging will take place at the residence location. The daily charging requirement E (kWh) is estimated by

$$E = \eta \times D, \tag{1}$$

where D is the daily driving distance, and η is the EVs specific consumption (kWh/km). In this paper, η is assumed to be 0.25 kWh/km as a worst case scenario, see [17] for elaborate estimates of η.

The model assumes that EVs have large enough batteries to meet their daily driving requirements. Such an assumption is motivated by the finding in [18], where the authors showed that the currently available EVs can meet the requirements of drivers with little adaption, e.g. 55 kWh battery could satisfy 88% of daily trips made by US drivers on a single charge.

The arrival time is randomly sampled from the recorded trips, in the travel survey, which ended at home. The model differentiates between weekdays and weekends, since they have different mobility behaviors as shown in Fig. 1.

The daily driving distance is calculated by doubling the random trip distance sampled from the trip distances of the recorded trips arriving at home [16]. This is assuming that each EV performs two equally long trips a day. The average weighted—based on weekdays and weekends—yearly driving distance was estimated to be 11,724 km/year, which is close to the recent estimates in Sweden, 12,000 km/year as of 2017 [19].

C. Smart charging methods

In this section the smart charging algorithms are described. Three different charging methods were compared in this paper. The first method is constant power charging, where an EV is charged using the peak capacity of the charger until the EV's daily energy requirement E (kWh) is fulfilled. The charging power P_{EV} (kW) at time t is defined by

$$P_{EV}(t) = \begin{cases} Cp, & \text{if } t_a \le t \le t_e \\ 0, & \text{else} \end{cases} \tag{2}$$

where Cp is the charging power, t_a is the arrival time, and t_e is the end of charging time using opportunistic charging estimated from

$$\int_{t_a}^{t_e} P_{EV}(t)dt = E. \tag{3}$$

The previous charging method is not limited by operational limits, e.g., house fuse size, grid limitations and EV battery limits to the charging power. This charging method is often called opportunistic, uncontrolled or dumb, charging in the literature, and is often used as a benchmark for the smart charging schemes. Similarly in this paper, the two proposed smart charging schemes are compared to this scheme.

Constant power charging can have adverse effects on the infrastructure. One of these effects is breaking the power fuse in the house. Peak power consumption in Swedish houses is limited by the distribution system operator's (DSO's) installed fuse. The second charging scheme, postponed charging takes this limitation into account by reducing the charging power when the total load of the house exceeds the fuse limit C_f (kW):

$$P_{EV}(t) = \begin{cases} \min\{C_p,\ C_f - P_h(t)\}, & \text{if } t_a \le t \le t_e \\ 0, & \text{else} \end{cases} \tag{4}$$

where $P_h(t)$ is the house load (kW) at time t. As indicated by the name, this charging scheme will postpone the charging when necessary to avoid breaking the fuse.

The third charging scheme, capacity-filling, makes the most of the available fuse capacity. In the capacity-filling scheme, the EV is charging with the difference between the fuse capacity C_f and the house load $P_h(t)$ at time t:

$$P_{EV}(t) = \begin{cases} C_f - P_h(t), & \text{if } t_a \le t \le t_e \\ 0. & \text{else} \end{cases} \tag{5}$$

This charging scheme does not constrict the charging power by the limits of EV battery on the charging power.

Fig. 2 presents a diagram representing the difference between the three proposed charging schemes. In Fig. 2a the constant power charging is presented. As shown, the total load of the house, $P_{EV}(t) + p_h(t)$, can exceed the fuse capacity, the yellow horizontal line. On the other hand, the postponed charging scheme ensures that the total load never exceeds the fuse capacity, see Fig. 2b. The capacity-filling charging scheme, on the other hand, does not limit the charging power, and instead fully utilizes the fuse capacity. The difference between the two schemes postponed charging and capacity-filling can be seen in the end of the first charging session in Fig. 2b and c.

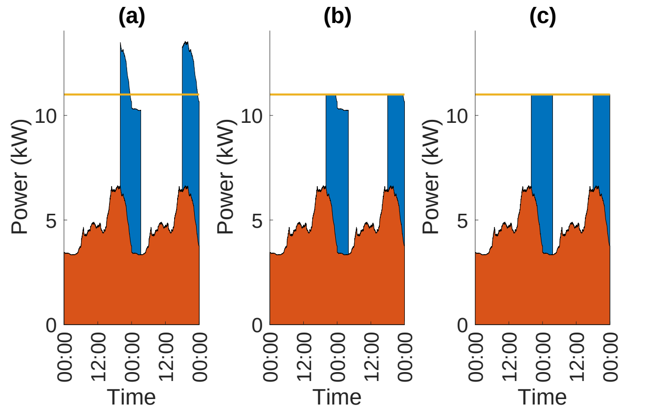

Fig. 2. A diagram representing the three compared charging scenarios in this paper: (a) constant power charging—uncontrolled charging, (b) postponed charging, and (c) capacity-filling. The orange area represents the house load, the blue represents the total load, including the charging load. The horizontal yellow line depicts the fuse size.

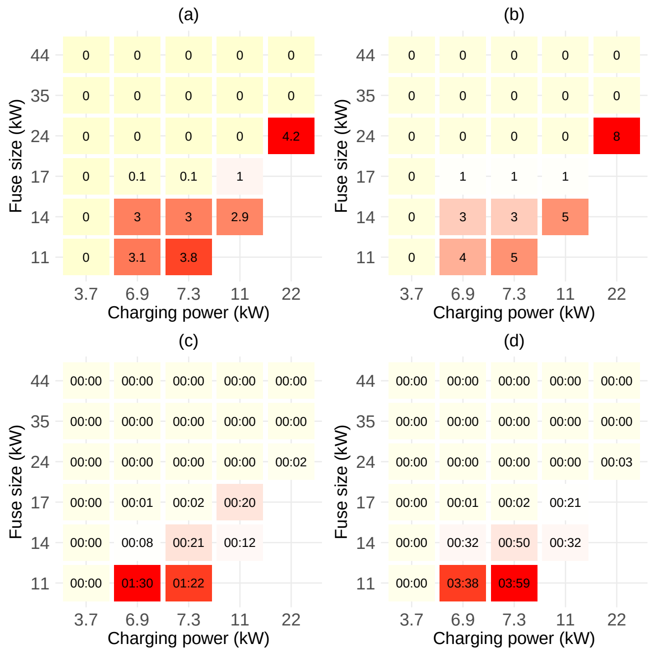

Fig. 3. Results of the postponed charging scheme for the different charging powers and the different fuse sizes. (a) Presents the average—among the 10 simulated houses—number of days per year where postponed charging events were needed, and (b) presents the maximum number of days year for the worst house—the house with the highest number of postponed charging events. The average increase in charging duration—compared with constant power charging—is presented in (c), and the maximum increase is provided in (d). Darker squares reflect less preferred results.

On the one hand, the postponed charging scheme is expected to increase the charging duration compared with the constant power charging scheme, and thereby cause inconvenience to EV drivers. On the other hand, the capacity-filling scheme can reduce the charging duration of the constant power charging scheme. This might take place when the fuse is large enough to charge with higher power than the EV charger capacity of the constant power charging scheme. Moreover, capacity-filling charging might also increase the charging duration if the fuse size is small such that the charging power is reduced below the constant power charger capacity. In this study, the EVs are assumed to remain connected to the charger until the end of the charging session regardless of the charging duration.

In this paper, five charging powers were compared; $C_p \in \{3.7, 6.9, 7.3, 11, 22\}$ kW each with charging rate of $\{0.25, 0.46, 0.49, 0.73, 1.47\}$ km/min. In addition, the simulated fuse sizes were the fuse sizes offered by a DSO in Sweden [20]; $C_f \in 11, 14, 17, 24, 35, 44$ kW. Simulation cases where the charging power was higher than the fuse size were excluded from the study, e.g., $(C_p, C_f) = (22\text{ kW}, 11\text{ kW})$ was excluded. The time-resolution of the model was minute based.

III. Results

This section presents the results of the simulation. The results of the postponed charging and the capacity-filling charging schemes are presented in Fig. 3 and in Fig. 4, respectively.

In Fig. 3a, the average number of days a year, for all the houses, in which postponed charging was needed to prevent the total load from exceeding the fuse size. At worst, the average number of days where postponed charging was needed was 4.2 days a year. This occurred when charging was done using 22 kW chargers and 24 kW fuse size. The authors also noticed that increasing the charging power sometimes reduced the average number of days where charging was needed, e.g., the 14 kW fuse with 7.3 kW and 11 kW charging power. This was a result of reducing the charging time, by increasing the charging power, and thus ending the charging before some load peaks occur. This phenomenon, however, was not observed in the remaining studied cases.

In Fig. 3b, the maximum number of days a year where postponed charging was used is presented. These results represent the worst case scenario of postponed charging that a single house might face. Controlled charging was not needed at all if 3.7 kW chargers were used—regardless of the fuse size. For the remaining charging powers, 8 days a year was the highest number of days in which inconvenience, due to postponed charging, took place.

Fig. 3c, depicts the average increase in the charging duration in comparison with the constant power charging. For example the 14 kW fuse size, as the charging power increased from 6.9 kW to 7.3 kW the average charging duration increased. This was due to the fuse size limitation. Nonetheless, as the charging power increased further to 11 kW, the days at which postponed charging was needed changed. The 11 kW chargers caused EVs to finish charging earlier than the house peaks in some days where the 7.3 kW charger caused the charging to coincide with these peaks. However, the 11 kW chargers caused load peak violations in new days at which problems were not observed using the 7.3 kW charger. Overall, the average increase in charging duration for the 11 kW charger was 12 min in comparison with 21 min for the 7.3 kW chargers.

Increasing the fuse size from 14 kW to 17 kW in case of the 11 kW chargers caused the average increase in the charging duration to increase from 12 min to 20 min. When the fuse size increased, the number of postponed charging sessions per year decreased—as shown in Fig. 3a. Nonetheless, the more extreme situations, which required longer

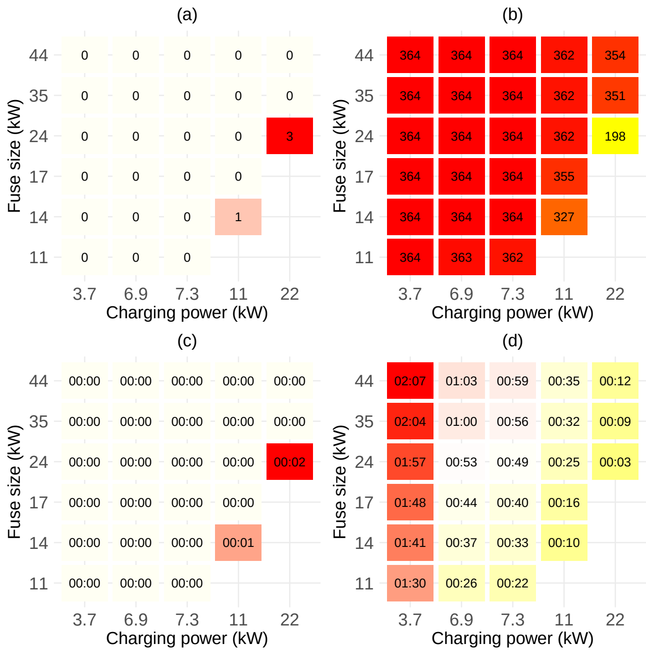

Fig. 4. Results of the capacity-filling charging algorithm for the different charging powers—when compared with constant power charging—and the different fuse sizes. (a) Presents the maximum number of days per year where charging duration increased—the worst house. (b) Presents the minimum number of days per year where charging duration decreased—the worst house. The maximum increase in charging duration is presented in (c), and the average decrease in charging duration is provided in (d). Note that the darker color is preferred in (b) and (d) while it is the opposite in (a) and (c).

charging durations remained thereby the average increase in the charging duration was higher for the 17 kW fuse size case compared with the 14 kW case.

Fig. 3d, depicts the maximum increase in the charging duration due to postponed charging. The worst house—the house with the maximum increase—suffered at most 4 hours of increase in its charging duration when charging using 7.3 kW and with 11 kW fuse. Nonetheless, a house with a fuse size of 17 kW will suffer at most 21 min of increase in the charging duration.

The results of the capacity-filling charging scheme are depicted in Fig. 4. Using this charging scheme, the charging time can decrease or increase in comparison with the constant power charging. It can decrease if the difference between the fuse size and load is larger than the charging power and increase when the opposite is true, see (5).

Fig. 4a shows that at most a house experienced 3 days a year where an increase in the charging duration took place. In all the cases but two, no house suffered an increase in the charging duration during the simulated year resulting from the smart charging scheme. In contrast, the worst house—the house with the least number of days—reduced its charging time in 194–364 days a year, as shown in Fig. 4b. The number of days depended on the charging power and fuse size. Still, in all but 5 cases the worst house reduced the charging duration—compared with constant power charging—more than 362 days a year.

The maximum increase in the charging duration was measured to be 2 min Fig. 4c. This is to say that in comparison with postponed charging—presented in Fig. 3d—capacity-filling charging decreases the inconvenience to EV owners. Moreover, capacity-filling charging reduces the charging time compared with the constant power charging scheme by on average 3 min–2 hours, depending on the studied case, see Fig. 4d.

IV. Conclusion

In this paper, minute load data from 10 houses were used to evaluate the performance of two proposed smart charging schemes. The first scheme, postponed charging, delays the charging of EVs if power violations occur. The second scheme, capacity-filling, charges EVs with the difference between the fuse size and the house load. Both schemes were benchmarked to the constant power charging—uncontrolled charging. The results show that the behavior of the charging schemes depended on the load of the house, the charging power and the fuse size.

With the postponed charging scheme, at most a house will suffer from the increase in charging duration 8 days a year. At most the charging duration increased by extra 4 hours. This is to say that the need for controlled charging in Swedish houses is almost negligible. Postponed charging was not required at all if EVs are charged using 3.7 kW chargers.

On the other hand, the capacity-filling charging scheme at most increased the charging duration 3 days a year, and it decreased the charging duration at least 198 days a year. The charging duration was reduced by on average 3 min–2 hours depending on the case.

The capacity-filling scheme is favored compared with the postponed charging—when each is compared to the constant power charging—as it is less likely to cause increases to the charging duration and it instead reduces the charging duration compared with the constant power charging scheme.

Future studies might investigate the impacts of the proposed controlled charging schemes on the electricity grid. In addition, future studies might add variable RES generation, e.g., photovoltaics (PV), to the house load. Studies employing smart charging to balance unbalanced 3-phase power consumption in houses are also left for future work.

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