Load Control of Residential Real Estate to Improve Circumstances for EV Charging

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***Abstract*—It is well known that uncontrolled EV charging may cause high peak loads and overloading. However, limiting the EV charging power may also reduce the total energy, which can be charged into the EV in a certain time period. This might raise concerns especially among full electric vehicle users as they cannot use traditional fuels e.g. gasoline to continue the trip after electricity runs out. In this paper, a control system which controls residential heating loads to enable higher EV charging powers without sacrificing comfort of living is introduced and discussed. Results of a real pilot system and two different simulations are presented. The results indicate that compared to the case with only EV charging current adjustment, up to around 30% more energy can be charged into the EV over a night by utilizing the presented control system.**

***Index Terms*—EV charging, Load control, Peak load limitation, Residential real estate**

I. Introduction

There have been growing interest in electric vehicles (EVs). Although the amount of EVs in Finland is still low, the amount has almost doubled each year during the past few years [1]. Typical residential real estate e.g. detached house may not be suitable for a new high-power load like uncontrolled EV charging. To reduce the risk of overloading, there are at least a few simple options e.g. utilization of slow one-phase charging or charging current adjustment of mode 3 charging. Mode 3 charging can be adjusted according to the main fuse and the real time current consumption of the real estate, which eliminates the risk of EV charging related overloading completely.

As full-electric vehicles (FEVs) cannot utilize alternative fuels to continue the trip after electricity runs out, it becomes more important to charge energy into the FEVs as much as possible. By limiting charging current too much, the FEV users may need to use public charging stations more often than necessary. This can be a concerning factor and reduce the adoption rate of the emission free vehicles.

In Finland, heating is likely to be one of the largest energy consumers of a real estate. Since delaying heating load e.g. for an hour may not have a notable impact on the comfort of living, electric heating can be utilized as a controllable load quite well. For the same reason, hot water heater can be used as a controllable load similarly. If these kinds of loads can be controlled optimally, the EV charging circumstances could be improved.

In the literature, there have been multiple studies related to EV charging in a residential real estate e.g. [2]–[6]. However, these studies focus mostly on energy cost minimization. In [7], domestic load management including EV charging control to limit peak loads have been discussed. To the best of the authors' knowledge, load control of a residential real estate to improve EV charging circumstances have not been studied properly. In this paper, the potential of a residential real estate heating load control to enable higher EV charging currents is investigated. A control system is developed and tested in a pilot case. Additionally, a simulation model of the control system is formulated. The performance of the control system is analyzed by examining the results of the pilot case and the simulation model.

The rest of the paper is organized as follows. Control method is introduced in section II. Pilot case and simulation model are described in section III. The simulation results and the pilot measurements are compared in section IV. In section, V the paper is finalized with conclusions and discussion.

II. Control Method

The fundamental idea of the control method is to keep available current for EV charging in the suitable range (e.g. 8–16 A) by controlling the controllable loads (e.g. electric heating and hot water heater). The available EV charging current capacity is the difference between allowed peak current and measured real time currents. In case of three-phase EV charging, the available EV charging current is the minimum available current of the three phase currents. This paper focuses on three-phase EV charging. However, the control method could be applied to one-phase charging as well. The information about the available EV charging current is transmitted to actual EV charging point at short time intervals.

According to standard IEC 61851-1 [8], the maximum AC charging current per phase can be adjusted between 6 A and 80 A in mode 3 EV charging. Since 25 A is a typical main fuse size in Finland, a charging point with maximum charging current below 25 A (e.g. 16 A) might be feasible. There have also been reports that some EVs cannot utilize currents lower than 8 A and thus the current which can be used for EV charging might be limited to 8–16 A. This acceptable charging current range is assumed within this paper. In addition to the minimum and maximum current, a target current is also included to the control method. This target current is used to determine if more controllable loads should be turned off to enable higher available EV charging current, or if some of the controllable loads should be turned on.

To secure comfort of living, there should be a limiting factor (e.g. timer) for each controllable load, which ensures that the load is not turned off too long. Depending on the nature of the controllable load and the required level of the comfort of living, acceptable controllability of the load may vary. Since there are multiple different potential use cases for the control system, it is important to retain flexibility. Different EVs can utilize different charging powers so the minimum and maximum current should be adjustable. The basic setup of the control system and a simplified block diagram of the most fundamental function of the control method are presented in Fig. 1 and 2 respectively.

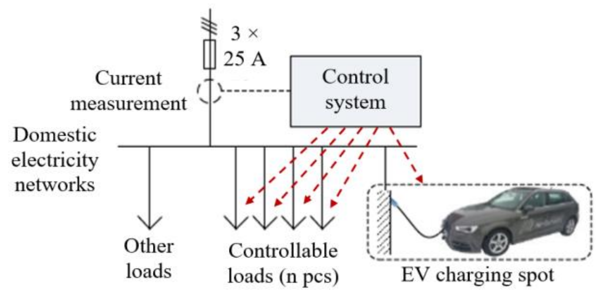

Fig. 1. The basic setup of the control system.

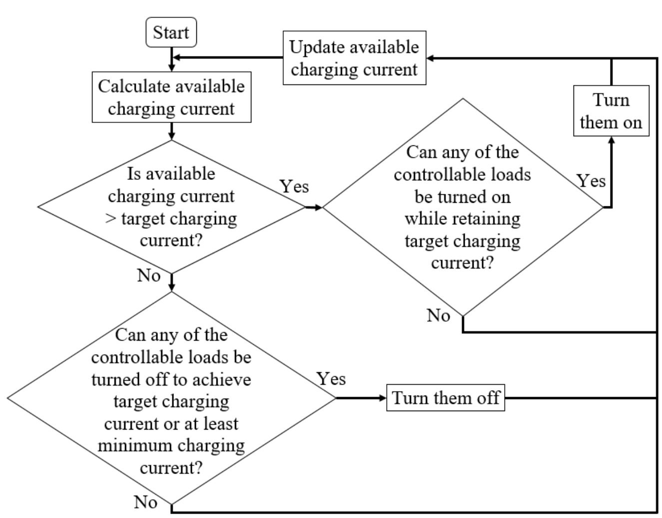

Fig. 2. Simplified block diagram of the main function of the control method.

By knowing the currents of the controllable loads, the control system can estimate new available charging current before the actual control action. However, the control system does not know whether the controllable load is on or off without separate feedback. To achieve lower investment and installation costs of the control system, separate feedbacks of the controllable loads are not considered in the control system in this paper. This can lead into a situation where the control system toggles a certain controllable load off which does not actually increase the available charging current as expected. However, this most likely does not have a notable negative impact as the control system can correct the potential problem in the next control cycle in e.g. 5 seconds.

III. Pilot Case

In order to approximate the usefulness and effectiveness of the control system, a pilot case was implemented. The pilot case is an electrically heated detached house located in Satakunta area in Finland. The main fuse size of the real estate is 25 A and there are 6 underfloor heaters and a hot water heater which can be used as controllable loads. There is a two-time tariff in use, and these controllable loads can be forced by a separate switch to utilize only cheaper night-time electricity. In case of a forced utilization of night-time electricity, the loads can draw power only during the night-time (22:00–07:00). The pilot case did not include actual EV charging. However, the pilot system was operated in a way that EV charging circumstances would be improved.

A. Preliminary Measurements

To enable comparison of the pilot case to the original situation, preliminary measurements of the real estate were conducted. Based on the measurements, it was possible to simulate different scenarios and approximate the energy which could be charged into the EV over a night.

The total currents of the real estate were measured over a one-week long period for each phase. During this one-week period, all underfloor heaters were forced to utilize only the cheaper night-time electricity. The hot water heater was used without this limitation the first four days (Monday–Thursday) but was toggled on for the last three days (Friday–Sunday) to utilize only night-time electricity. This way the typical peak loads in both situations could be observed.

According to the measurements, the average current over the whole week for phase 1, 2, and 3 were 3.3 A, 5.9 A, and 7.0 A, respectively, whereas the highest one-hour peak currents were 20.0 A, 21.1 A, and 13.8 A, respectively. The measurements show that the night-time consumption is already relatively high without EV charging and thus uncontrolled EV charging may cause overloading.

During, e.g., Friday-Saturday, there won't be almost any current capacity left for three-phase EV charging around midnight when hot water heater is on simultaneously with space heating loads. Regardless of the utilization of night-time electricity, similar situation could occur anyway, and thus uncontrolled three-phase charging is inadvisable. The preliminary measurements indicate that around 12 A one-phase charging would be possible for the phase 3. This would occasionally cause minor overloading but might not trip the overload protection as the standard SFS-EN 60269-1 (IEC 60269-1:2006) defines that a fuse with a nominal current (In) between 16 A $\leq I_n \leq$ 63 A should withstand a current of $1.25\times I_n$ for an hour (in 20 °C ambient temperature).

The current consumption of each controllable load was also measured separately. These are presented in Table I. It can be seen that most of the controllable load capacity is connected to phases 1 and 2, whereas the phase 3 has highest average loading.

TABLE I. PROPERTIES OF THE CONTROLLABLE LOADS

Load	Phase	Current consumption (A)
Underfloor heater 1	1	4.8
Underfloor heater 2	1	8.4
Underfloor heater 3	2	6.2
Underfloor heater 4	2	4.9
Underfloor heater 5	3	4.5
Underfloor heater 6	3	3.3
Hot water heater	1 and 2	6.9 and 7.1, respectively

B. *Simulation Model*

To evaluate the effects of different parameters and to demonstrate the operation of the control method before testing the pilot system, simulation model for the pilot house is formulated. Since the preliminary measurements of the pilot case only included the total phase currents of the real estate, the exact energy consumption of the controllable loads could not be deduced. Therefore, assumptions and simplifications have to be made in the simulation model. However, even a rough model enables estimating the operation and potential benefits of the control system.

Firstly, the hot water heater is not modeled as a controllable load as it is problematic to determine when it is on and off. For simplicity reasons, the controllable loads are assumed to be on during the night-time if the related phase current is over a certain threshold. Since the space heating is restricted to utilize night-time electricity only, it could be determined that the space heating is off during daytime. These thresholds ensure that the controllable loads will not be considered being on if the related phase current is not high enough. The downside of this assumption is that e.g. underfloor heater 1 is considered being on more than underfloor heater 2, which may not be the case. The thresholds are chosen based on the current consumptions of the controllable loads and the minimum currents of the corresponding phase. The thresholds have been presented in Table II. The assumption on how the controllable loads is on have been illustrated in Fig. 3.

If a certain controllable load is turned off by the control system to allow higher EV charging current or to limit peak loads, the control duration is calculated. In order to ensure the required level of the comfort of living, the duration of the off period is to be restricted using an adjustable timer. Depending whether the controllable load would be otherwise on or off, the missed heating duration is calculated and used to achieve the same indoor temperature later. In the simulation model and pilot system, the maximum control duration of each controllable load is limited to 2 hours per a four-hour period. For simplicity reasons, it is assumed that the load control only delays the amount of heating. The fact that indoor temperature may slightly decrease during the load rescheduling and thus longer period of heating might be required afterwards to achieve the same peak indoor temperature is not considered in the simulation model.

TABLE II. SIMULATION ASSUMPTIONS OF THE CONTROLLABLE LOADS

Load	Phase	Current threshold (A)
Underfloor heater 1	1	4.8
Underfloor heater 2	1	13.2
Underfloor heater 3	2	6.6
Underfloor heater 4	2	11.5
Underfloor heater 5	3	5.5
Underfloor heater 6	3	8.8

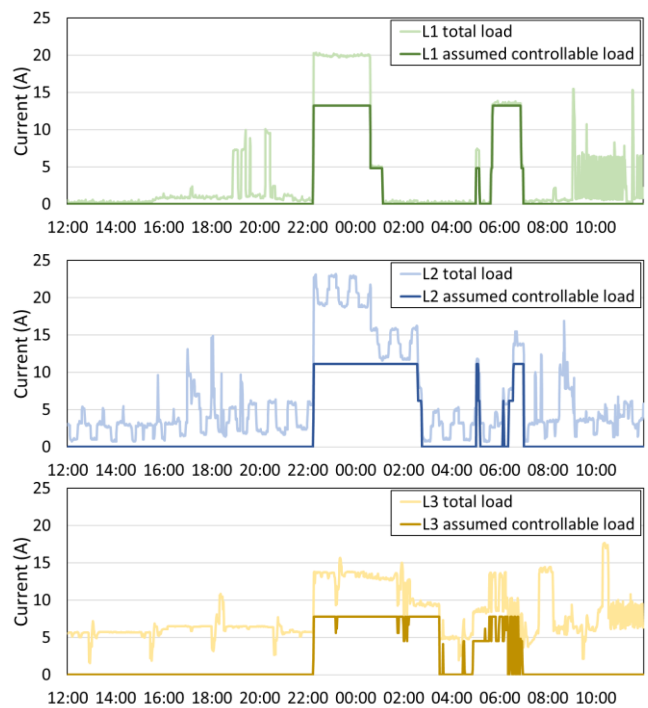

Fig. 3. Currents of the controllable loads on Friday–Saturday in the simulation model.

The impact of the control method is presented in Fig. 4. In Fig. 4, the maximum allowed total current of the real estate is 24.9 A and the target EV charging current is 12 A. Therefore, the control method attempts to limit phase currents to 12.9 A by rescheduling the controllable loads if necessary. If any of the phase currents rise above 16.9 A, there will be less than 8 A available EV charging capacity and thus EV charging must be halted. The available charging duration is assumed to be from 18:00 to 06:00. Fig. 4 shows that some of the controllable loads will be scheduled after 07:00. If the heating of the property is utilizing night-time electricity only, the heating load occurring after 7:00 would actually be scheduled to the later periods of the day, after 22:00. This may cause lower room temperatures. This could be solved e.g. by estimating the delayed heating load and restricting the EV charging current before morning to enable enough heating. However, this is not taken into account in the simulation model nor in the pilot system.

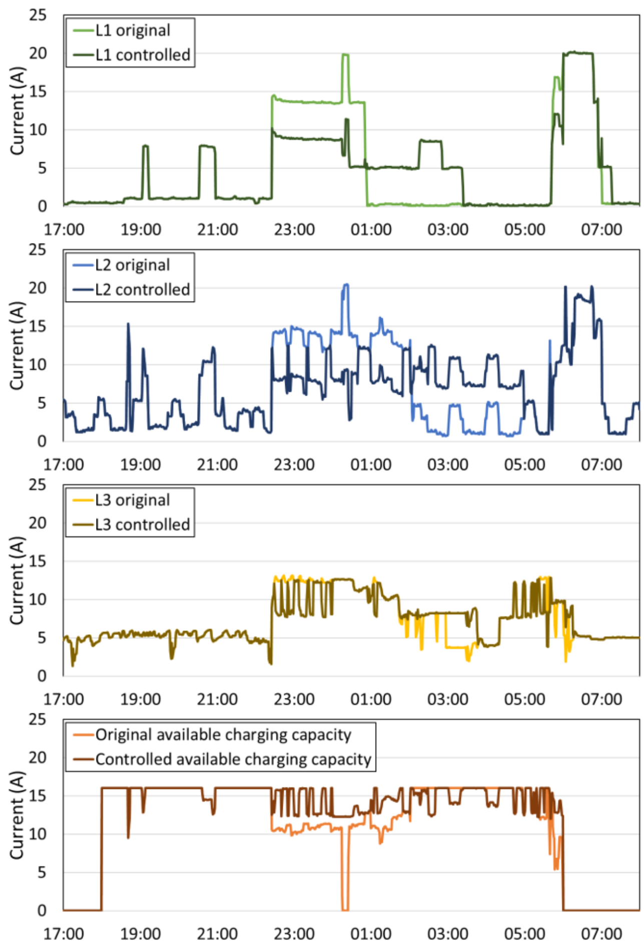

Fig. 4. Simulation results of the rescheduling of the controllable loads on Wednesday–Thursday in case of 24.9 A maximum total current of the real estate and 12 A as target EV charging current.

C. *Pilot System*

The pilot system consists of an automation system which controls 7 contactors, one for each controllable load. The controllable loads are still controlled by the original thermostats, but the pilot system is able to delay the heating loads when necessary by controlling the contactors. The pilot system utilizes the previously mentioned control method (illustrated in Fig. 2) and the system is tested in four different scenarios which are described in the next section.

IV. Results

The idea of the pilot case is to test the core functions of the control system and estimate the benefits. Based on the measurements and simulations, four test scenarios are chosen. These scenarios have been presented in Table III. The duration of each scenario is around 72 hours, and the EV charging is assumed to be conducted between 18:00–06:00.

The effectiveness of the pilot system and the accuracy of the simulation model is assessed in the following subsections. All scenarios are investigated by comparing three cases:

1. Pilot system measurements
2. Results of the simulation model
3. Without heating load control

In case 3, the heating loads are not controlled but the EV charging current is simply assumed to be adjusted according to the free capacity. Cases 2 and 3 are based on the preliminary measurements and thus there is likely to be some differences on the electricity consumption of the real estate compared to the pilot measurements. However, the average outdoor temperature was similar during the preliminary measurements and the pilot system testing (around 0˚C). For better comparison, same weekdays are chosen for each case. Available charging energy is calculated using a voltage level of 230 V and assuming that the EV could utilize any charging current between 8–16 A.

TABLE III. Test Scenarios for the Pilot System

Scenario	Forced night-time electricity utilization	Total current limit of the real estate (A)	Target current of EV charging (A)
1.	Hot water heater and underfloor heaters	24.9	12
2.	Only underfloor heaters	22.5	10
3.	Only underfloor heaters	20.0	9
4.	None	18.0	9

To examine the comfort of living, floor temperatures were measured from several different locations before and during the pilot system testing. The temperature measurements were conducted in the morning and the results indicate that the pilot system did not have noticeable impact on the temperatures in any of the following scenarios. The variation in the floor temperatures were mostly within ±0.5˚C range from the preliminary measurements.

A. *Scenario 1*

The idea of the scenario 1 is to utilize night-time electricity as much as possible for controllable loads and EV charging without risk of overloading. In Fig. 5, one-minute averages of the phase currents and available charging current of the pilot system case have been presented. It can be seen that the phase currents are kept relatively steady through the night and there will be plenty of available charging capacity during the whole charging period. The numerical results for this scenario are presented in Table IV.

When comparing the case without heating load control and the simulation model, it can be seen that heating load controlling enables around 6.8% (7.8 kWh) higher EV charging energy. This percentage is relatively low due to the fact that average EV charging current over the charging period is already close to the maximum and the charging current does not need to be restricted very much. In the pilot system, the energy consumption is 21.7% (10.9 kWh) higher, but the available EV charging energy is about the same than in the case without heating load control.

TABLE IV. RESULTS OF SCENARIO 1

	Pilot system[a]	Simulation model[a]	Without heating load control[a]
L1 (A)	6.0	4.0	4.0
L2 (A)	8.0	6.8	6.9
L3 (A)	8.2	7.3	7.3
Available charging current (A)	13.9	14.8	13.9
Available charging energy (kWh)	114.8	122.8	115.0
Required charging interruption (min)	3.8	0.6	17.6

a. Daily average values of the three charging periods (18:00–06:00) between Monday–Thursday. The maximum current of the real estate and the target charging current were 24.9 A and 12.0 A, respectively.

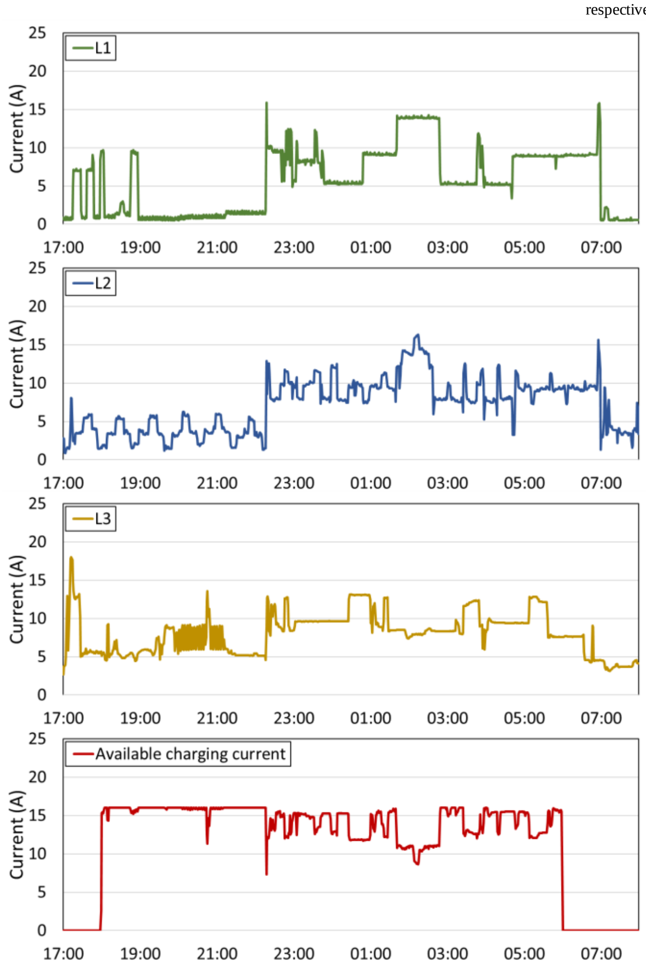

Fig. 5. Measured currents of the real estate and the available EV charging capacity in the pilot system case on Wednesday–Thursday.

B. *Scenario 2*

In scenario 2, the peak current is limited to 22.5 A. According to the preliminary measurements, the real estate peak current average of one-hour period are 20.0, 21.1, and 13.8 for phases 1 to 3, respectively. Therefore, this peak current limitation could be possible regardless of the heating load controlling if the EV charging current is controlled.

The energy consumption of the simulation model is around 8.1% (5.1 kWh) lower than in the case without heating load control, which means that the control system is scheduling the controllable loads partly outside of the investigated charging period (18:00–06:00). Also, the control system allows about 18.8% (16.2 kWh) more energy to be charged to the EV when comparing the simulation model to the case without heating load control. In the pilot system, the energy consumption of the real estate is 6.0% (3.4 kWh) and 13.6% (8.5 kWh) lower than in the case of simulation model and the case without heating load control, respectively. However, the available EV charging energy is also 6.1% (6.3 kWh) and 26.0% (22.5 kWh) higher, respectively.

Lower energy consumption of the real estate during the pilot system case is likely because the hot water heater is utilizing only night-time electricity between Friday–Sunday during the preliminary measurements. For a better comparison, the results of Thursday–Friday are investigated separately and presented in Table V.

From Table V, it can be seen that while the energy consumption of the real estate is 11.7% (6.6 kWh) higher in the pilot system case than the case without heating load control, the available charging energy is 4.3% (4.3 kWh) higher for the pilot system. When comparing the simulation model case and the case without heating load control, 10.9% (6.2 kWh) of the total load is scheduled outside of the investigated charging period and 16.1% (16.1 kWh) higher charging energy is achieved.

TABLE V. RESULTS OF SCENARIO 2 ON A SPECIFIC DAY

	Pilot system[a]	Simulation model[a]	Without heating load control[a]
L1 (A)	6.6	4.1	4.4
L2 (A)	9.0	6.4	7.2
L3 (A)	7.3	7.8	9.0
Available charging current (A)	12.6	14.0	12.1
Available charging energy (kWh)	104.1	115.9	99.8
Required charging interruption (min)	14.8	0.3	53.5

a. Daily average values of the charging period (18:00–06:00) between Thursday–Friday. The maximum current of the real estate and the target charging current were 22.5 A and 10.0 A, respectively.

C. *Scenario 3*

The idea of the scenario 3 is to investigate if the peak currents could be limited to 20.0 A, which is less than the peak-hour current of phase 2 in the preliminary measurements, while allowing reasonable amount of energy to be charged into EV. In Table VI the results of scenario 3 is presented. According to the pilot system measurements, currents for phases 2 and 3 are successfully limited to 20.0 A. However, the peak average current of a one-hour period for phase 1 was 22.0 A. According to the data collected from the pilot system, this unexpected peak current could have been avoided. Due to unknown reason, the pilot system was not able to schedule the controllable loads of phase 1 to a later time period.

TABLE VI. RESULTS OF SCENARIO 3

	Pilot system[a]	Simulation model[a]	Without heating load control[a]
L1 (A)	5.1	4.0	4.0
L2 (A)	6.5	6.6	6.9
L3 (A)	6.0	6.9	7.3
Available charging current (A)	11.5	11.7	9.1
Available charging energy (kWh)	94.8	96.6	75.0
Required charging interruption (min)	80.3	30.9	236.3

a. Daily average values of the three charging periods (18:00–06:00) between Monday–Thursday. The maximum current of the real estate and the target charging current were 20.0 A and 9.0 A, respectively.

In scenario 3, the simulation model schedules 4.8% (2.4 kWh) of the real estate load outside of the investigated charging period and enabled 28.8% (21.6 kWh) higher EV charging energy. In pilot system case, the energy consumption is 3.9% (2.0 kWh) lower but the available EV charging energy is 26.4% (19.8 kWh) higher when compared to the case without heating load control.

D. Scenario 4

In scenario 4, the aim is to reduce peak currents even more by allowing all controllable loads to utilize also daytime electricity. The pilot system results cannot be compared properly to the simulation model or to the case without heating load control since the preliminary measurements were not conducted for this kind of scenario where all controllable loads could utilize either night-time or daytime electricity.

According to the pilot system measurements, the peak currents were successfully limited to 18.0 A while reasonable amount of energy could have been charged into the EV. This suggests that even higher peak power reduction could possibly be achieved with the control system in the pilot case.

V. CONCLUSIONS AND DISCUSSION

The core function of the presented control system is to limit peak currents while improving the circumstances for EV charging. Besides the unexpected peak current in scenario 3, the pilot system executed the core functions well. Since the energy consumption of the real estate vary from day to day, the accuracy of the simulation model cannot be directly proven by comparing current consumptions of the pilot system and simulation model. However, the results of the pilot system and simulation model in scenarios 1–3 are at least somewhat in line with each other even though the simulation model included a few simplifications.

When comparing the scenarios 1–3, it can be seen that the control system is more effective compared to the case without heating load control when the real estate energy consumption is relatively high compared to the peak power limit. In the selected scenarios, the heating load control enabled around 6–30% more energy to be charged to an EV. It should be noted that different EVs can utilize different charging currents and thus the actual gain may vary even more.

While enabling higher average charging powers, the control system can also limit peak loads and provide better utilization of cheaper night-time electricity. In addition to eliminating the risk of overloading related issues, the peak load control can bring operational cost savings if a power-based tariff component (€/kW of some period) is used by the distribution system operator. According to [9], these kinds of demand-based distribution tariffs are likely becoming more popular as they are potentially more cost-reflective than the present distribution tariffs of small-scale customers.

In each scenario, the potential charging energy is quite high, around 50–120 kWh. This would be more than enough to fully charge a typical FEV. However, the assumed 12-hour charging period may not always be possible and thus the potential charging energy may be notable lower. Depending on the driving requirements and available charging time, the control system could, for example, reduce the need to use public charging stations notably.

Encouraged by the good results, an application for a patent was filed [10]. The intention is to continue developing flexible energy management systems suitable for different real estates.

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