CONTROL OF ELECTRIC VEHICLE CHARGING IN DOMESTIC REAL ESTATES AS PART OF DEMAND RESPONSE FUNCTIONALITY

Antti RAUTIAINEN, Kimmo LUMMI, Pertti JÄRVENTAUSTA
Tampere University of Technology – Finland
antti.rautiainen@tut.fi

Ville TIKKA, Andrey LANA
Lappeenranta University of Technology – Finland
ville.tikka@lut.fi

ABSTRACT

The paper discusses an electric vehicle (EV) charging control method enabling flexible high-power charging in domestic real estates. In the method, the charging current(s) of an EV is adjusted in accordance of the free capacity between maximum current limit and the non-EV load current(s). This kind of charging is simulated using long-lasting electricity consumption measurements and is also demonstrated with a real commercial charging station and an EV. The simulations and the real world demonstration show that the method works well and is very flexible. However, if it is widely used, its impacts on distribution grids are not favorable from distribution system operator (DSO) point-of-view. Power based distribution tariffs, which are nowadays under active consideration by Finnish DSOs, could cope with this problem.

INTRODUCTION

Electric vehicles (EVs) offer a new, or historically speaking a retro type, tool to decrease CO_2 and air quality related emissions, reduce oil dependency and even to improve operation of the electric power system. Over the past few years, almost all big car manufacturers have brought different types of EVs to the markets, and some new players like Tesla Motors have reached significant momentum in the EV business. Perhaps the greatest barrier to widespread penetration of EVs today is their high prices. It is however probable that the prices go down in the following years.

EVs are a new type of a load in electricity networks. EV charging load has different impacts in different types of networks like transmission networks, distribution networks and networks of real estates. Over the last few years, lots of research has been conducted on impacts of EVs in transmission and public distribution networks, but the research lacks studies of EV and peak power/current related problems and their solutions in the networks of domestic real estates like detached houses. For charging station groups some work has been made in [1]. In spite of increasing number of public charging stations, significant part of charging will be made also at homes [2]. In many households where electric vehicles are charged, a question “how large charging current can I use?” arise. With the present distribution tariff structures of small consumers, there are mainly two limiting factors: capacity of the network connection (main fuses) and capacity of the feeder feeding the charging station. In many houses especially equipped with electric heating and electric sauna stoves, there is significant variation in the load levels. At some points of time, there is a great possibility to use large charging currents of EVs, but occasionally the free capacity is very small. This is especially true in households with 3 × 25 A main fuses. This main fuse size is a very common, probably the most common one, in Finland in detached houses and especially in newest ones. This paper investigates a simple control method in which charging current(s) of the EV is continuously adjusted in accordance with the free current capacity of the phase(s) in order to keep the total current(s) below the maximum current limit. The method also presents a tool to be used in different domestic demand response applications. The paper includes discussion, simulation and demonstration results. In the simulations, the benefit of the method is quantified, and in the demonstration the method is tested with a real commercial EV and charging station in order to verify the method in general and to see the dynamics of the charging current controller of an EV.

THE CONTROL METHOD

Fig. 1 illustrates the main principle of the control method. If an EV is brought to a household network, there is a significant possibility that at some points of time, the current rating of the main fuses is exceeded. The idea of the control method is that the total current of the network connection is measured in real-time, and the charging current of the EV is adjusted based on the free current capacity of the network connection. This kind of control is possible in a mode 3 charging in accordance of the standard IEC 61851-1, which defines that the charging station can restrict and adjust the maximum AC charging current between 6 A and 80 A. The standard is highly respected and is applied practically in all commercial EVs. The control method can be applied for one-, two- and three-phase charging.

There can be different requirements for the current control dynamics. From technical point-of-view, commonly used gG main fuses tolerate quite high overcurrent before blowing. Standard IEC 60269-1:2006 (EN 60269-1:2007 in Europe and SFS-EN 60269-1 in Finland) defines that fuses with nominal current (I_n) of 16 A $\leq I_n \leq$ 63 A have to tolerate (at 20°C ambient temperature) current of $1.25 I_n$ for one hour, but during the one hour long test the fuse must blow with a current of $\geq 1.6 I_n$. In addition, the standard defines current and time pares (so called "ports") for faster blowing with higher currents. From another point-of-view, DSOs in practice require that in case of appliances which are used "often", the currents should not exceed the rating of the network connection [3]. With the present smart meters in Finland, this is hard to supervise. However, it can be considered that it is always safe to try to restrict the phase currents of the network connection to the nominal current, although it is possible in practice to take currents higher than the main fuse rating.

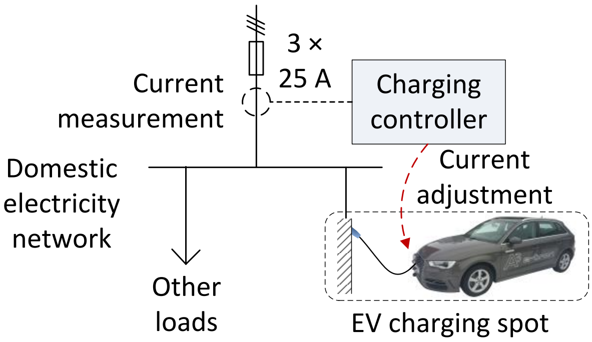

Fig. 1. The basic setup of the control method.

SIMULATION DATA AND MODELING

In order to know how big a benefit one could get of the EV charging control method, simulations were carried out based on long-term electricity consumption measurements made in a real household. The measurement equipment measured the phase currents and the currents of individual feeders from the main switch gear of the house. Measurement equipment recorded current samples in 6 s intervals for 3.12.2014–16.5.2015 (165 days). The house is a detached house (137 m^2 living area) with an electric heating system (heating cables in the floor). The annual electricity consumption of the house is of the order of 16 MWh/a.

In the simulations, charging of an EV with a three-phase 3 × 32 A charger was modeled in the house. The main fuse size of the house is 3 × 25 A. The simulation use case was to charge the EV with the highest possible charging current without blowing the main fuses. In the simulations, the blowing of the main fuses, or at least the risk that the fuse(s) might blow, has to be modeled somehow. In this case, a simple rule was applied. As mentioned earlier, the gG fuses have to tolerate current of 1.25 times the nominal current for 1 h. With a higher current the fuses might blow. In the simulations, a sliding time frame of the latest hour was analyzed during every time step of the simulation, and if the time integral of $I(t)^2R$ (where R is the resistance of the main fuse) of the simulated current $I(t)$ reached the level of the time integral of $(1.25\ I_n)^2R$ during the time frame, it was deduced that there is a risk that the fuse will blow. This rule simplifies some things such as the real ambient temperature of the fuse etc., but using the rule the risk of fuse blow is modeled in a fair way.

A charging process was modeled for every day of the 165 day long measuring period. For simplicity, it was assumed that the charging would be started every day at 17:00 and the charging need of the EV would be 40 kWh. This is a realistic number as for example in the highest range version of *Tesla Model S* the battery pack has 90 kWh capacity. The starting time and the energy need of the EV are arbitrarily chosen numbers, but give a good picture of the phenomenon. In the simulations, six different charging cases were calculated. In the cases 1–5, constant three phase charging currents of (3 ×) 6 A, 10 A, 15 A, 20 A and 25 A were applied, and in the sixth case the controlled charging method was applied so that a 25 A maximum phase current limit was given to the charging system.

SIMULATION RESULTS

Figures 2 and 3 show one example of the charging simulation. The upper part of Fig. 2 shows the phase currents (without charging) during one charging event. It can be seen that there are some points of time where the currents exceed the 25 A main fuse size even without charging. The middle part of the figure shows the 10 A charging current. The lowest part of the figure shows the total current. In this case, there is a risk of fuse blow, and it occurs first time at 21:57. The high "base" load is mostly caused by the 10.5 kW (3 × 15.2 A) electric sauna stove. Fig. 3 presents the charging and total currents of the same time frame but with the controlled charging case. It can be seen that in this case, charging is much faster and there is no risk of fuse blow.

A summary of the simulation results can be seen in Table 1. The upper part of the table shows the number of charging events in different cases in which there is a risk of main fuse blow. One can see that only with the lowest possible charging current (6 A) there is no risk of fuse blow. When the charging current is higher, the number of possible fuse blows increase. The lower part of the table presents the average differences of charging times between the constant current and the controlled charging cases. In these numbers, only the charging events where there was no risk of fuse blow were taken into account. In the 6 A, 10 A and 15 A cases the controlled charging was faster than in the constant current charging case. For example, the controlled charging time was 2.78 h (2 h 47 min) faster on average compared to the use of 10 A constant charging current. In 20 A and 25 A cases the charging can be faster than in the controlled case, but the risk of fuse blow is very high.

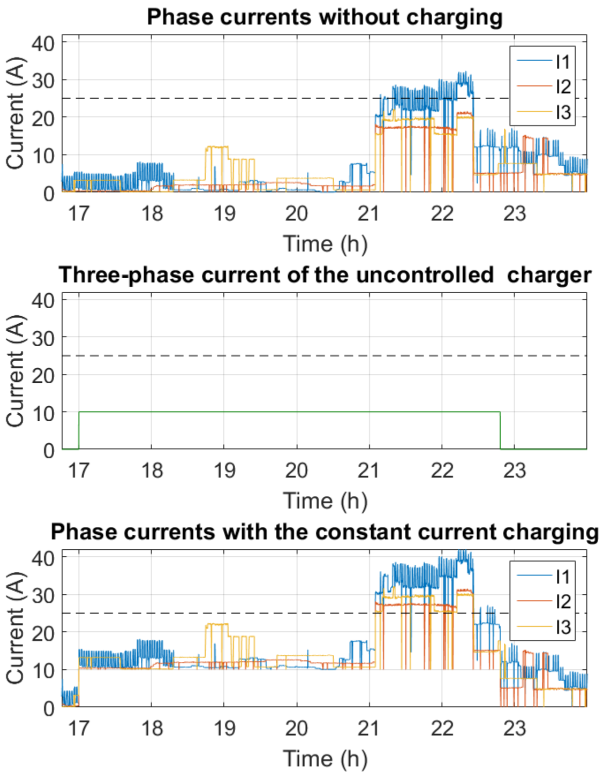

Fig. 2. Simulation results with a 10 A constant charging current.

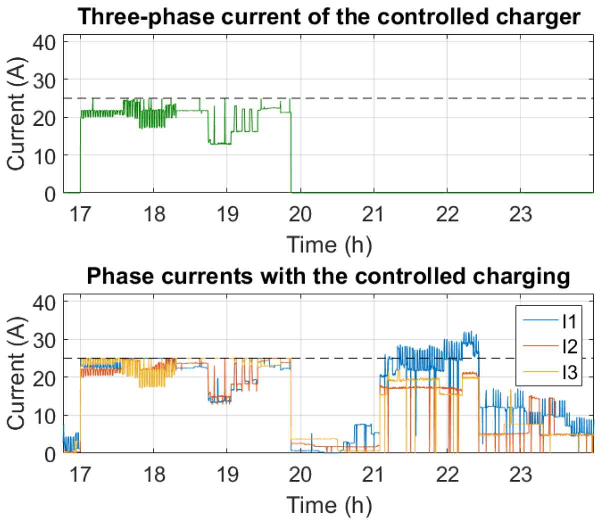

Fig. 3. Simulation results with the controlled charging current.

Table 1. A summary of the simulation results.

Constant charging current	6 A	10 A	15 A	20 A	25 A
Number of possible fuse blows	0	1	5	16	70
The average difference of charging times compared to the controlled case (h)	6.65	2.78	0.88	–0.02	–0.47

DEMONSTRATION

In addition to simulations, a real life demonstration with commercial charging station and a commercial EV was made. The demonstration illustrates the use case where one-phase EV charger is brought to a real detached house, and the charging current is controlled in order to keep the phase current below the rating of the main fuse. In the demonstration, the charging station was 3 × 32 A AC charging station from *Ensto*, and the EV was *Audi A3 e-tron* plug-in hybrid EV. The EV and the charging station are presented in Fig. 4. The EV has a one-phase charger with 15 A maximum current. Further, phase current (one second average RMS values) of one phase (I_{base}) of a real Finnish detached house with main fuse size of 3 × 25 A was measured. After this, the maximum charging current (I_{max}) of the EV was adjusted in real-time to be $I_{max} = 25\text{ A} - I_{base}$. In practice, the maximum current was adjusted using serial port communication to the commercial charging station based on the measurement.

Fig. 4. The EV and the charging station of the demonstration.

The results of the demonstration are shown in Fig. 5. In the figure, the following quantities are shown as a function of time: the base current (other loads besides the EV) of one phase of the detached house, the calculated maximum charging current limit, the measured charging current of the EV and the total current of one phase of the house (sum of the base current and the charging current). In all the subfigures, a horizontal dash line represents the 25 A phase current limit. One can see that the variations in the base currents are very high. The computational maximum current limit was given to the charging station and further to the EV, but as the EV has only 1 × 15 A charger, the charger takes 15 A at the highest. It can be seen from the results, that the charger reacts rapidly to the changes in the maximum charging current limit. The time difference between the change in the limit and the change in the current is roughly of the order of two seconds in both directions of the change (decrease and increase of the current).

One can also see from the Fig. 5 that there are some points of time where the 25 A total current has been exceeded. This is because the limited speed of the charging current control system. When a rapid increase in the base load occurs (in Fig. 5, due to on/off switching of electric sauna stove), it takes some time from the charger to decrease the current. However, the exceeding times are very short, some seconds at the maximum. Overall it can be said, that the control system works very nicely also in real life.

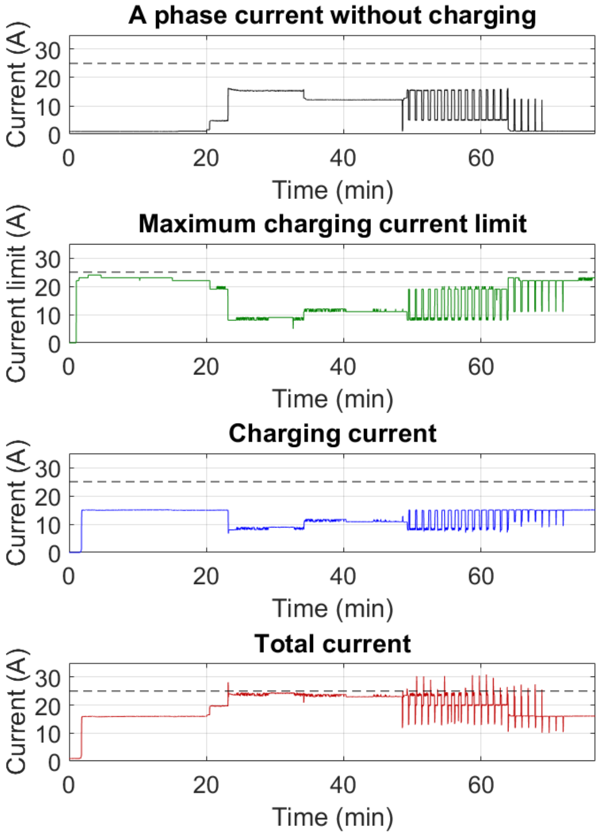

Fig. 5. The results of the demonstration.

DISCUSSION

The results of the paper show that the charging control method can greatly enable a flexible and a safe way to charge EVs as fast as possible in the domestic charging station. The control method is suitable for many kinds of domestic real estates. The simulations show that if there is often a need to charge large amounts of energy rapidly to an EV, the control system shortens the charging times significantly and makes the charging also safe from the overcurrent protection point-of-view.

However, widespread application of the method would cause some problems. If there were large amounts of EVs with high-power charging at homes using the whole capacity of the network connection for many hours on daily bases, it could dramatically increase the loads (some cases even unsymmetrically) in the distribution networks. This could be problematic from DSO point-of-view, and as in the end the network customers pay all the additional investments in via their distribution tariffs, the additional costs would be posed to the network customers themselves. This means that with present tariff structures also the network customers without EVs would pay for the additional investments. A possible solution for this could be that the DSOs could launch new types of distribution tariffs which would include some kind of a power/peak power based component [1]–[2],[4]–[7]. Today in Finland, such types of tariffs are not yet used for small network customers, but are under active discussion and research. These kinds of tariffs would offer the network customers to use the whole capacity of their network connection, but higher power demand would result in a higher distribution fee. If the distribution tariff structures would mirror the cost structure of the DNO in a better way than present tariffs, this could lead to a more optimal solution for the customer. It is also noticed that the charging control method discussed in this paper could also be used as a tool for demand response in order to minimize the charging costs by adjusting the charging current in accordance with some kind of an electricity price signal.

REFERENCES

[1] A. Rautiainen & P. Järventausta, "Load control system for an EV charging station group", in proc. of Nordac 2014 – 11th Nordic Conference on Electricity Distribution System Management and Development, Stockholm, Sweden, 11 p.

[2] A. Rautiainen, 2015, "Aspects of Electric Vehicles and Demand Response in Electricity Grids", *Doctoral Thesis*, Tampere University of Technology. Available: http://URN.fi/URN:ISBN:978-952-15-3615-1

[3] Finnish Energy organization,"Network service conditions recommended by Finnish Energy organization 2014", 19 p., (In Finnish), Available: http://energia.fi/sites/default/files/verkkopalveluehdot_vpe_2014_20160118.pdf

[4] P. Mandatova, M. Massimiano, D. Verreth, C. Gonzalez, 2014. "Network tariff structure for a smart energy system", in proc. of Cired Workshop 2014, Rome, Italy, 4 p.

[5] Eurelectric, 2013. "Network tariff structure for a smart energy system". Eurelectric, 30 p.

[6] Energy network association (ENA), 2014. "Towards a national approach to electricity network tariff reform", ENA Position paper, December 2014, 40 p.

[7] K. Lummi, P. Trygg, A. Rautiainen, P. Järventausta, "Implementation possibilities of power-based distribution tariff by using smart metering technology", in proc. of Cired 2015, 23rd international Conference on Electricity Distribution, 2015, 5 p.