Case Study: Smart Charging Plug-In Hybrid Vehicle Test Environment with Vehicle-To-Grid Ability

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Keywords

«Electric Vehicle», «Hybrid Electric Vehicle (HEV)», «Charging Infrastructure for EV's», «Energy system management», «Smart Grid»

Abstract

The aim of the paper is to describe and introduce smart charging test environment and plug-in hybrid vehicle capable of smart charging and vehicle to grid functionality. Furthermore, the paper aims at demonstrating simple smart charging strategy in operation on smart charging test bed. The demonstration utilizes commercially available components and open source programming solutions. Charging strategy demonstration is a combination of actual hardware operations and stochastic sampling to synthetize driving cycles of the electric vehicle. Driving behavior synthetizing is based on national travel survey data to ensure reasonable driving behavior in testing of the smart charging strategy. The main outcome of the paper is the description of an actual smart charging test environment. The results also suggest that the charging strategy targeting to minimization of the charging costs may not be feasible for a single customer or single end user. However it must borne in mind that the electricity retailer (or market aggregator) may see some feasible incentives in smart charging strategies based on market price control.

Introduction

The number of electric vehicles (EV) is slowly increasing while also the green ideology seems to be gaining a stronger foothold in the political field in Finland. Based on the scenarios presented in [1], a substantial number of EVs will be on the road by 2020, in Finland. Moreover, the emissions targets of the European Union are driving towards less polluting society. In the field of transportation, EVs are among the most promising alternatives to strive towards CO_2 free transportation. As the previous studies [2] and [3] suggest, the grid effects of the EV charging will have a substantial impact on grid loads, and therefore, all alternative charging schemes have to be studied. The main concern is simultaneous charging of a large number of EVs which may pose a considerable threat to the electricity distribution networks. Among the most discussed charging strategies, the strategy aiming at lowest charging cost from socio-economic perspective is the preferable choice. Such a strategy can be understood simply aiming at minimizing the cost of electricity or with more sophisticated manner, aiming at total cost minimization. The total cost minimization covers elements such as loss power cost, electricity cost, grid (capacity) cost and charging equipment cost. In the paper the aim is to describe and verify the functionality of the charging strategy aiming at the lowest electricity cost, because, the main aim of the paper is verify functionality of smart charging test bed, rather than demonstrate highly sophisticated charging strategies.

Some special cases such as spot price controlled charging may result in undesirable effects to the grid, such as peak load growth. For instance, if a large group of electric vehicles are controlled based on the price signal, it could result into a case in which the majority of the charging loads become concentrated on the same hour. Furthermore some of the smart meter functions may enable even more flexible loads that may behave similar as EV charging load, in the near future. Thus, it is essential to investigate the effects of such charging control algorithms. Furthermore, it is essential to develop pilot systems that can support testing of such control systems. Pilot systems also produce user experience data that can also be seen valuable as smart charging may and will need some input parameters from the user. For instance, typically the car is used only an hour per day. However, when usage occurs the car has to be ready for use. Therefore the car user should have the possibility to give the system an initial estimation of the usage time instances or requirement on the state-of-charge (SoC). Real-life demonstrations are needed to validate the theoretical charging strategies.

Testing of the charging strategies on test bed neither solves, nor gives answers for all of the questions posed. For instance, controllable loads are capable of posing unpredictable load behavior in the distribution grids. At least load may seem to behave unpredictably if observed from other than market aggregators' perspective. For instance, if electricity retailer has control privilege of some of the loads, electricity distribution system operator (DSO) may see the load vary unpredictably or unnaturally. Issue becomes even more difficult if DSO is given control privileges of the load, as it ruins the electricity retailer's balance between forecasted and realizing electricity demand, resulting in higher balance settlement cost.

From the DSO's perspective market price controlled charging may appear as a treat to the grid, because loads might overlap more than natural behavior would suggest. For instance, grids are typically dimensioned based on some confidence level, so that the line sections are not selected to withstand theoretical maximum loads (sum of maximum loads of each individual customer). In a LV transformer circuit of 30 household customers, the dimensioning load may be only fifth of the theoretical load. It has to be borne in mind that the dimensioning power is not only technical dimensioning, but a techno-economical compromise. In practice this, means that the grids are not that likely to be overloaded. Load over dimensioning criteria cause loss power to increase, and when loss power increases also loss power cost increases. Equation guiding the dimensioning of the grid is be presented as follows:

$$\min \int_{t_0}^{t_1} (C_{\text{investm}}(t) + C_{\text{loss}}(t) + C_{\text{intr}}(t) + C_{\text{oper}}(t))dt, \qquad (1)$$

where,

C_{investm} = investment cost
C_{loss} = cost of losses
C_{intr} = cost of interruptions
C_{oper} = cost of operation
Δt = planning period.

According to the equation, grid development is dependent of the expected load behavior that should be known as well as possible. The typical planning period of the distribution grid is tens of years. Therefore the pilot projects are in crucial role in the strategic planning of the distribution grids.

In the paper, the charging load is optimized based on the electricity price information and demonstrated with the real-life case on actual test setup. The electricity cost minimized charging does not solve problems of increasing grid load but could still be an option for the end customer. It is likely that electricity price controlled charging appears as a conflict of interest between distribution system operator and electricity retailer. This conflict of interest is discussed briefly in the case of smart charging of EVs. The conflict of interest in a demand response application is studied in [4]. Grid effects and modeling of EV charging is discussed in [6]-[11].

The key elements of the study are:

- Demonstration of smart charging test bed in action
- Demonstration of electricity cost minimized charging
- Definition of data requirements for smart charging scheme considered
- Studying of the conflict of interests between the DSO and the electricity retailer

Simulation Setup

Pilot demonstration aims at providing a platform for testing of the smart charging strategies. Furthermore, the vehicle to grid (V2G) functionality is considered as part of the smart charging properties. In other words the test platform has capability of feeding electricity back to the grid. Pilot demonstration is based on modified Toyota Prius Plug-in-Hybrid Vehicle (PHEV). The vehicle has been updated with an additional LiFePo battery pack the capacity of which is 4.6 kWh . The battery pack is connected to the hybrid drive battery with a 13 kW DC/DC converter which provides power for highway cruising. In addition, the vehicle is equipped with two 500 W inverters to achieve vehicle-to-grid functionality with maximum in-feed power of 1 kW. The nominal power of the on-board battery charger is 3 kW and it is controlled by the battery management system of the additional LiFePo battery pack. The battery charger is only used to charge the additional LiFePo battery, not hybrid system battery.

The smart charging management is conducted with an industrial PC running Linux operating system. The physical control is handled by the relay control board connected to the on-board PC. The on-board PC has CAN bus interface for the car, and thus, it is capable to poll values from the information system of the vehicle. The on-board PC is also used to maintain the automatic driving diary as vehicle is driven. Charger management connects to a charging pole via power line carrier (PLC) modem. The charging pole has simple Linux based interface operating as a proxy between the pole and the vehicle. The charging pole routes communication requests directly to a Linux server running the energy management system (EMS). The EMS server maintains MySQL database where data of each event is stored. For instance, when car plugs in, the EMS server updates database item flag to active. Vehicle's driving history is stored on the server also. The communication from the car's on-board PC to EMS server is operated via Ethernet by TCP/IP protocol.

The main purpose of the smart charging pilot has been to develop test bed for the functionality testing rather than develop fine tuned product for the end user, and thus, the communication between units has been conducted by robust TCP/IP commands that could be send directly to the desired unit. For instance, the charging management could set the EV to discharge. It is possible to develop and run different smart charging schemes on the test setup.

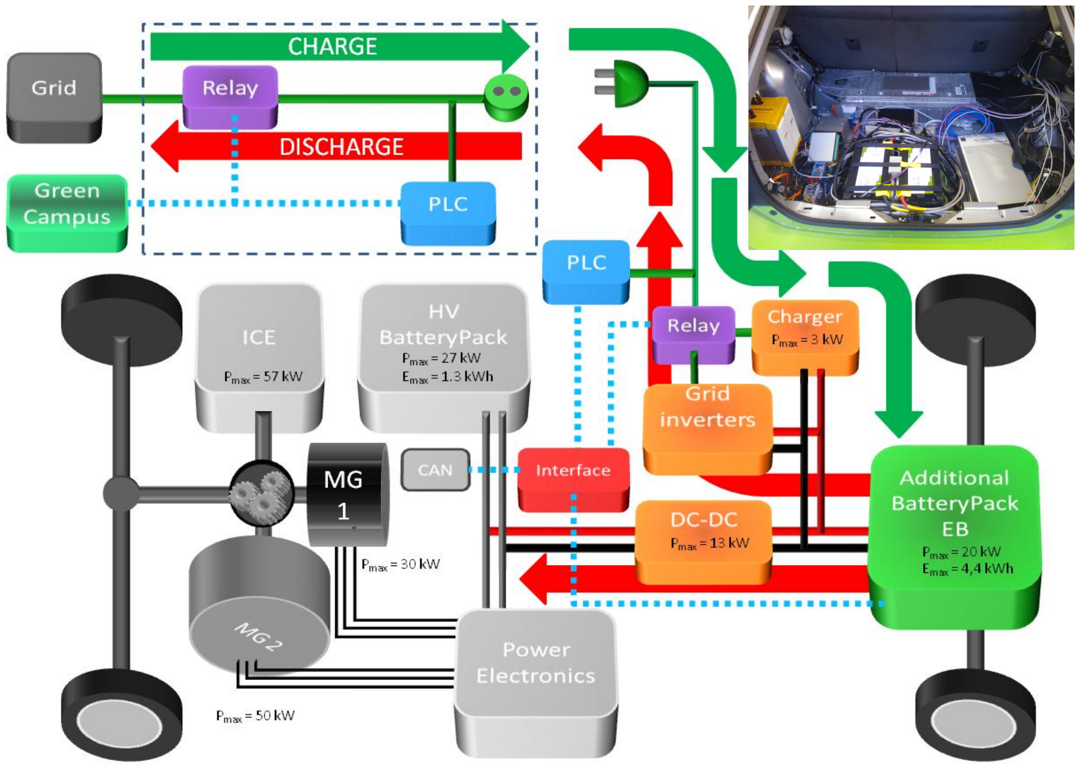

Fig. 1: Test setup, batteries, BMS, charger and inverters.

The aim of the paper is to demonstrate the operation of the price signal controlled charging . Driven mileage and availability (duration the car is connected to the charging point) of the car is synthetized by sampling the departure time, arrival time and average daily mileage from the distributions acquired from the National Travel Survey (NTS) of Finland [5].

Required Data for the Smart Charging Interface

The smart charging scheme needs data from several different sources to operate efficiently. Depending of the charging strategy, requirements on the data sources and time criticality vary. For instance, some of the grid support functions may need almost real-time data, while market price strategies can operate with delays ranging up to hours. In the paper, the electricity price optimized charging is considered, and therefore, the management of the charging necessitates hourly electricity tariff from the Nord Pool Spot.

The working environment in the paper is Nordic area, and therefore, Nord Pool Spot is considered as a source of the price signal. The Nord Pool market consists of two physical electricity trades; day-ahead and intraday markets. The day-ahead market for the next day, and the bids must be submitted before 1 pm in Finnish time (+3h GMT) [12]. After the bids have been submitted the market is closed and day-ahead prices are published based on crossing point of supply and demand of the each hour. The intraday market begins after the day-ahead market is closed. The operation is similar to day-ahead market, but intraday market closes for each hour just before delivery. The Nordic market is divided into the different price areas. For example, the area price in Finland may differ from the Nordic system price in the case of power flow congestions.

Spot price for the next day is public information and can be obtained directly from the Nord Pool website with a scheduled script and stored on the EMS server's database. In the simulation Finnish area price is used.

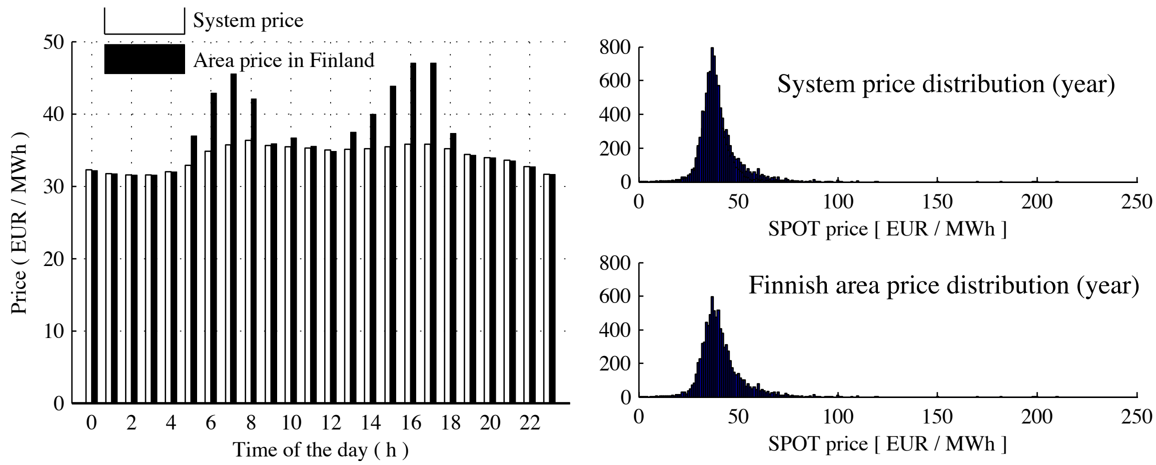

Fig. 2: Example of SPOT price over a day and price distribution over a year 2013.

The smart charging strategy needs also data concerning the vehicle to be charged. For instance, it is vital to know the duration of the charging and restrictions that user may have set. In the paper, one case deals with the case in which the user of the vehicle has option to set the time when the charging event should be finished. In that case, the user of the vehicle is considered to have standard daily working hours from 8.00 am to 16.00 pm and the charging is set to be finished at 7.00 am.

Vehicle also delivers nominal values of the charger to the EMS server so that the charging management is capable of estimating the required charging time for fully charged battery pack. Vehicle can also deliver SOC value and nominal charging power for more sophisticated optimization strategies such as demand management and grid support applications. In the case demonstrated, the nominal charger power is set to 3 kW, even though the charging power may vary during the charging event. Typically the charging current of the LiFePo batteries may vary quite heavily as a function of temperature, to maintain the performance of the battery. In Nordic environment, heating of the battery may also be necessary before the charging begins. Therefore, LiFePo -cells cannot be charged on sub-zero temperatures. Vehicle also delivers other miscellaneous values for the EMS server. More specific description can be found in [13], where demonstration environment is presented in more detail.

Smart charging algorithm

In the paper the smart charging is considered as electricity price minimization. Optimization goal can be simplified as follows:

$$\min c_{\mathrm{tot}} = \int c_{\mathrm{e}}(t)dt \tag{1}$$

where

t = time

c_{e} = cost of electricity

The cost of the charging energy is minimized over time $t_1 \ldots t_2$. The t_1 is defined by the arrival time or current time. The t_2 is defined by the availability of the Nord Pool Spot price data or user defined "ready time" (set by the user/driver). For instance if cost optimization algorithm runs at noon, the Δt is limited to

12 hours ahead or to the user set time earlier. In the case optimization runs at 6 pm, the day-ahead SPOT market data should be available and minimization window could reach 24 + 6 h ahead (unless user has set earlier "ready time"). The actual charging management algorithm runs on MATLAB platform. Management algorithm runs inside infinite loop and refreshes values to be stored every minute. Charging strategy algorithm gathers all the necessary data from the EMS MySQL database by using Perl-functions. Charging control is conducted with robust TCP messages to EMS server. Message includes ID of the desired vehicle or other unit connected to the EMS and status to be set to the unit. Status can be set to idle, charging and discharging in the case of the PHEV test setup. The algorithm can be described by simplified block diagram format as Fig. 3 illustrates.

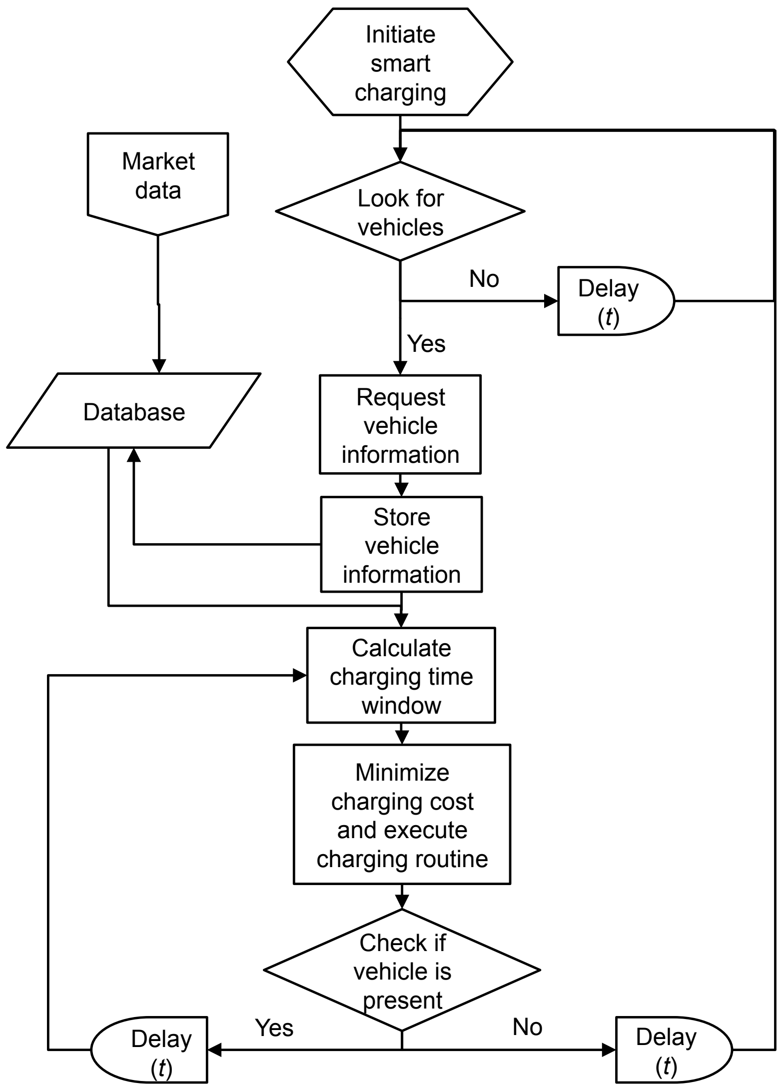

Fig. 3: Basic principle of the smart charging algorithm.

The charging control diagram does not describe the whole test procedure, as there are some stochastic sampling involved as well. The driving behavior is modeled rather than actually conducted by driving the vehicle. The actual vehicle usage could have lead to behavior that does not present average vehicle user. The more suitable solution is to synthetize driving behavior by sampling random events from the distributions acquired from the National Travel Survey conducted in Finland.

The travel survey can provide distribution for departures from certain typical trips such as from homes to working places or grocery stores. The daily driving distribution can be acquired as a sum of all the trips during a day. The data consist of thousands events collected during years 2010 –2011. Fig. 4 illustrates cumulative distribution of trip lengths used in synthetizing driving cycles.

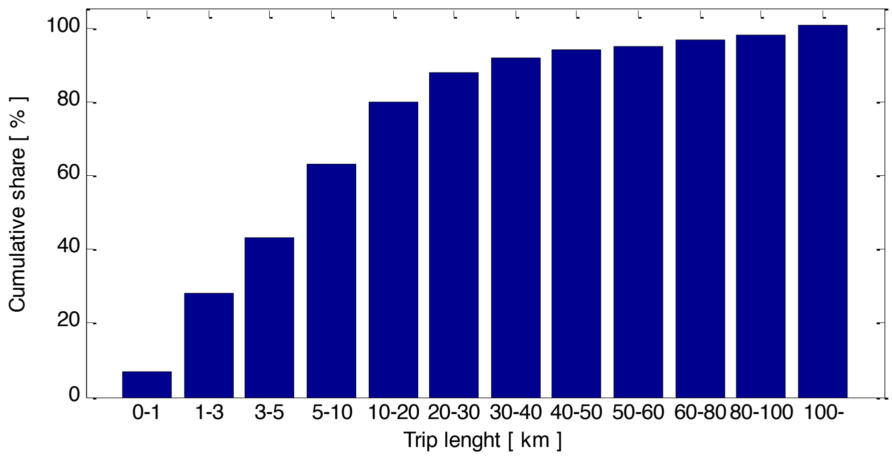

Fig. 4: Cumulative distribution of trip lengths driven in Finland. 80% of daily trips are less than 20 km.

Pilot system in the operation

The system has been in operation for a week. The main purpose of the demonstration was to test algorithm and communication, in practice. The vehicle was not driven during the test period so that the battery could be discharged at any time by the V2G function. In addition, the vehicle was held in controlled environment to ensure safe operation of the charging system. The driving does not give any surplus value for the test. In addition, the synthetized driving cycles can be assumed to represent average driver better than researcher driving the car. The driven mileage was randomized based on the NTS data by extracting distributions of average behavior and then sampling event from the distribution. The average daily total mileage in Finland is around 50 km/d per car, but for persons driving a car average total mileage is about 29 km/day/person. There are more than 4 million persons whom are considered in NTS study and about 2 million cars in Finland, thus mileage for the car is higher than average mileage per person driving a car.

The charging window was set to be randomly sampled, similarly as the mileage. Distributions were acquired from the NTS data and time of return was then randomly sampled. The “ready time” was set to 7 am to ensure that the car is fully charged when departure should happen.

Table I: The charging assumption.

Vehicle user type	Average workign person (defined due to random sampling)
Charging place	Home
Charging power	3 kW (nomimal)
Charging 'ready time'	7 am
Charing scheme	Electricty cost minimization
Price signal	Finnish area price (Nord Pool Spot)

The charging control algorithm was executed on MATLAB workstation that was operating as centralized control for the vehicles. The smart charging test was conducted over a week test period and data was collected during that time. Fig. 5 shows charging power over the week test period.

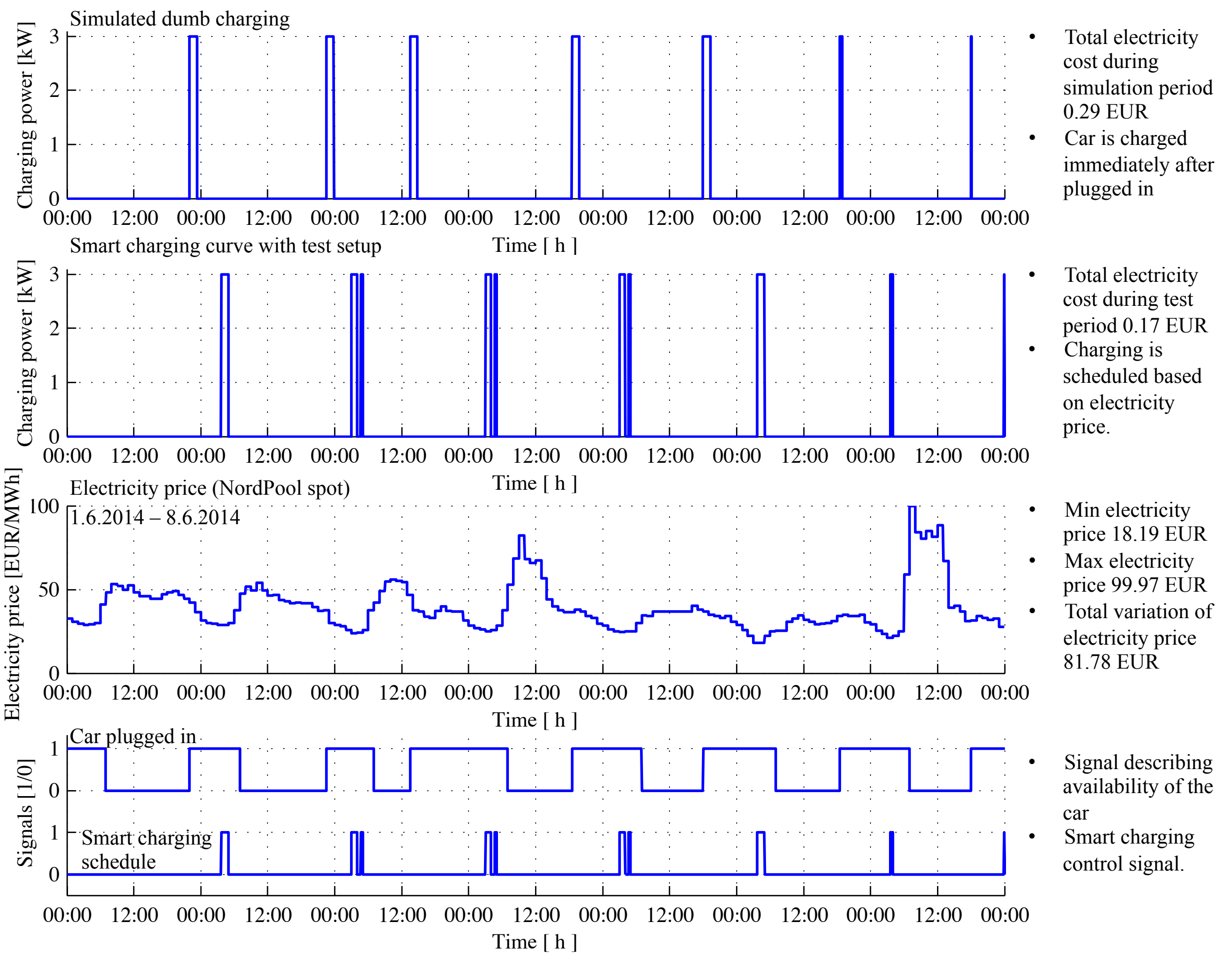

Fig. 5: EV charging curve over test period of a week.

In the first graph of the Figure 5 is shown simulated dumb charging strategy as a reference. The actual smart charging strategy conducted on the test bed is shown on second graph from top. It can be noticed that in the dumb charging scheme it is assumed that car is charged immediately after plugging in by nominal power of 3 kW. The total electricity cost in the case of the simulated dumb charging is 0.29 € per week. The actual smart charging scheme tested on the test setup resulted total electricity cost of 0.17 € per week.

In the smart charging strategy it is assumed, that the charging takes place when the Nord Pool Spot price is at the lowest and charging window is met. If demand of the charging energy is higher that can be charged during an hour, the second charging event takes place when the Nord Pool Spot price is at the second lowest level, and charging window is met. The length of the charging event changes as the charging demand is different for each day.

The total saving potential can be estimated based on the assumption that EV would have been charged right after arrival to the charging pole. The total saving of the test period is 0.11 €/week, equaling 6 €/a. It must be borne in mind that the saving potential is highly dependent on the electricity cost variation, and such a generalization of the annual saving potential should not be interpreted as the one and only truth, but more like guideline showing roughly what the saving potential could be. The more relevant result is the validation of the control strategy, which has been shown to operate over test period. Initial testing before the week test period showed, that communication and error handling is of great importance in the smart charging applications. For instance, the communication system and applications must be capable of handling short disturbances in the communication network. The latency of the communication line was not in critical role in the case test, but should be investigated more carefully for the applications that are more time critical.

Brief Discussion of the Conflict of Interests

There exists a conflict of interest between the DSO and the electricity retailer. In the Nordic countries, the DSOs operate in a monopoly position under a national regulation model, but the electricity retail market is liberalized since 1995 in Finland. It is in the DSO's interest to aim at the highest possible peak operating time, and thus, the grid should be exploited as effectively as possible, even though the reformed structure of the wholesale market has decreased the incentive to directly control loads [14]. On the other hand, electricity retailers probably have different goals depending on the product they are offering. For instance, balance settlement would create an incentive to control some of the loads to find a balance between the estimated and realized consumption or end users electricity cost minimization many cause high peak load to distribution grid. These goals are not usually in line with the DSO's load control targets that are based on the grid load.

The electricity retailer could have an incentive to control loads in the case of some unusual or unpredicted change in the consumption. The electricity retailers operate in a day-ahead market, and thus, the load has to be forecasted a day before the consumption takes place. The load forecast accuracy may be affected by several factors; for instance, adverse weather or an accident may cause traffic jams, and thus, people may arrive home later than expected. There has to be a balance between the consumption and the forecast to maximize the retailer's profit; to this end, the load control of the EVs would provide an ideal opportunity to shift loads to meet the forecasted load as closely as possible. Or in case cost minimization load forecast problem might even vanish. If the base load is shifted several hours later, probably there are few EVs already in the area waiting to be charged. On the other hand, the electricity retailer might aim at a positive error if the power balance in the grid requires down-regulation. If excess power is bid into the regulation market, the profit may be higher than the matching consumption forecast would have delivered. The described control scheme could be seen as a demand response power resource. The paper focuses on investigating a control scheme that aims at the lowest spot price of electricity, but in future, the actual control might be dependent in several other factors also. The question of further studies is: what are products electricity retailer can offer for the end user?

Results

The main result of the paper is the description of the fully operating smart charging system in laboratory environment. The results also show that the smart charging strategy tested in the paper can be implemented with only a few data sources. Operation of the charging strategy aiming at lowest electricity is proven to be functional. However, feasibility of the charging strategy cannot be well justified. The overall saving in the charging cost over a week test period was 0.11 €. In comparison to system cost savings are nearly irrelevant and highly dependent on electricity price.

Conclusion

The paper describes charging strategy aiming at electricity cost minimization conducted on smart charging test bed.
As a main result, the smart charging strategy is shown to be operating on actual test vehicle. Furthermore, the results suggest that savings earned by using the charging strategy aiming at lowest electricity price are negligible. But if considered in larger scale, also the electricity retailer may have interest into controlling of the charging. For instance, demand response applications may emerge as new opportunities in field of

smart charging. The system described in the paper could be operated based on the aggregator's commands, but also working on its own. To conclude, the paper delivered early stage description of the smart charging test bed and described simple smart charging strategy in operation. It is question of further studies, what kind of control strategies should be tested and what communication should exist between EVs (or energy storages, in general) and related data sources. The testing period emerged question of charging power estimation, because charging power is highly dependent on environment condition. In the case presented in the paper, tests were conducted in well-controlled environment. In practice ambient temperature may vary, and therefore, result decreased charging power due to restrictions posed by the LiFePo cells. It is question in the further studies: how charging power should be estimated and could heating be used to compensate ambient temperature changes?

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