A Simulation Environment for Electric Vehicle Charging Infrastructures and Load Coordination

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Abstract: The rollout of electric vehicles substantially changes the requirements for current power grid infrastructures. The high power demand of fast recharge stations in combination with a high risk of simultaneity leads to the necessity of extended ICT integration into the energy distribution process. This paper describes ongoing research on a simulation framework for modeling the communication processes of load coordination scenarios for (fast-) recharge stations. First results are presented for a fair distribution algorithm in a manageable scenario with simultaneously charging electric vehicles in order to validate the simulation environment.

1   Introduction

The broad introduction of Electric Vehicles (EVs) has a major effect on today's power grid infrastructures. Currently introduced AC-based charge stations already provide up to 44kVA power output. Even though the batteries and charge controllers of currently available EVs limit power consumption levels for recharging to about 10kVA, the charging power will increase in the medium term. Considering today's dimensioning of local power network stations in urban areas and in case of a high simultaneity factor for power demand, the introduction of an uncoordinated fast recharge infrastructure would inevitably increase the risk for local substation blackouts. Due to the high investment costs being involved in extending the power grid's capacities and more importantly taking into account that this extension is only needed for covering the peak loads during highly simultaneous power demand, extending the grid in terms of power output capacities does not seem reasonable and economically justifiable. Hence extending the use of ICT [WSM09] for scheduling and distribution of power consumption levels among consumers seems reasonable, especially when fast recharge stations for EVs are utilized simultaneously.

This paper presents ongoing work on a simulation framework allowing to model simultaneous charging processes of multiple EVs. It focuses on the communication process for balancing the power demand of a set of recharge stations in the domain of a local energy substation. In the following chapter the general simulation model is described. It focuses on the message exchange pattern for load coordination and describes all entities involved in the simulation model in more detail. Chapter 3 presents first validation results derived by the simulation framework for a load coordination scenario. Finally chapter 4 concludes this work and provides an outlook on future research.

2 Simulation Model

The presented simulation framework is based on OMNeT++, an event-based network simulation engine [VH08]. The current simulation model consists of three main entities: the Electric Vehicle (EV), the Charge Point (CP) and the Load Coordinator (LC). All these entities are based upon the same layer 1-4 setup provided by the standard INET framework [INE10] available for the OMNeT++ environment. For the moment layers 1 and 2 are based on the IEEE 802.11g protocol stack. Future work will consider Powerline Communications for layers 1 and 2 currently being discussed in [V2G]. Layer 3 and 4 utilize a standard TCP/IP stack with mobile ad-hoc network (MANET) routing functionalities and UDP on the transport layer. In order to consider mobility scenarios in future work, OLSR [CJ03] is used for route generation and therefore a mobility option based on [WPR+08] is included in the EV model. The charge controller as well as the battery model are implemented as dedicated applications in the EV model. The CP and the LC models are both represented as single applications on layer 7. Figure 1 gives an overview of the simulation model.
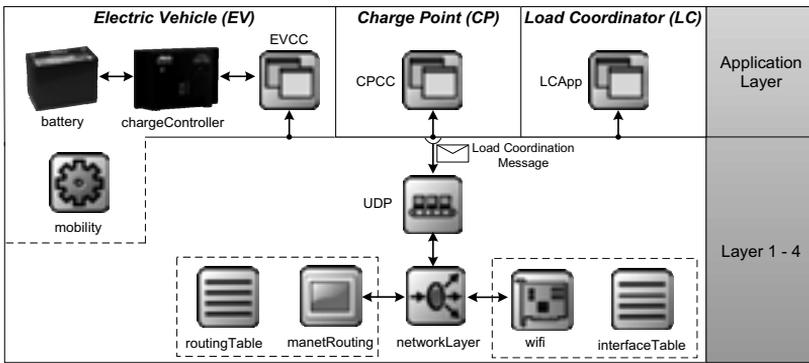

Figure 1: Overview of the Simulation Environment for the EV Charging Process

A load coordination protocol tailored towards the OMNeT++ environment has been designed describing the communication patterns between all entities of the simulation model. All currently respected fields of the message pattern are shown in figure 2. The pattern will be extended with respect to the high level communication protocol of [V2G] in the future. At the moment the EV reports the minimum and maximum charge current (`minI(int)`, `maxI(int)`) as well as an approximation of its parking duration (`duration(double)`) to the LC.
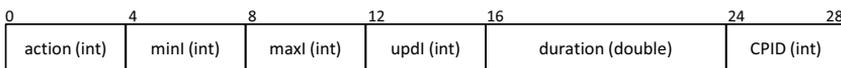

Figure 2: OMNeT++ based Load Coordination Protocol

The *Electric Vehicle Communication Controller (EVCC)* is the central communication module of the EV and is implemented for communication between the EV and the CP. It mediates between the internal modules of the EV and the charging infrastructure. It establishes the connection to the CP when the EV is plugged-in and requests a charge token from the CP as shown in figure 3(a). The CP is modeled as a gateway and appends its identifier (`CPID(int)`) to charge token requests and forwards them to the LC. The LC calculates available power capacities for each CP and replies with a charge token to the origin of the request and subsequently sends charge updates to all other CPs (see figure 3(a)).

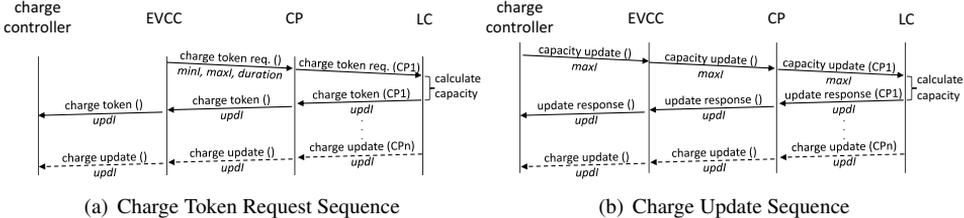(a) Charge Token Request Sequence

(b) Charge Update Sequence

Figure 3: Charge Token Request and Charge Update Message Exchange

All other internal modules of the EV (battery and charger) are implemented as traffic generators for the communication processes. Current EVs typically use high performance lithium ion (Li-ion) batteries. Figure 4(a) shows the charging characteristic of a Li-ion battery. When the battery is fully discharged it needs a pre-conditioning charge with a minimal current until a deep discharge threshold is reached. From this point the battery can be charged with constant current until it reaches its maximum cell voltage. In the third stage the battery will be charged with constant voltage leading to a decreasing charge current.

In figure 4(b) the charging characteristics of the simulated battery model are illustrated. The gradients of the voltage graphs in stage 1 and 2 are constant. In stage 3 the charging current is modeled as discrete saturation curve. This assumption is made because it has no major effect on the characteristics of the modules with respect to traffic generation. The battery model in the simulation environment can be parameterized regarding the following characteristics: battery capacity, min./max. charge current, max. charge voltage, number of phases, deep discharge threshold and the relative starting point of each stage regarding the total charge duration. With variable starting points it is possible to skip specific stages and charge a battery respecting only a single stage. This flexible parametrization allows other battery characteristics and charger types to be simulated with this environment in the future.

In order to control the charging process of the battery a *charge controller* has been added to the EV model. During the initialization of the simulation environment it obtains the battery parameters from a configuration file and initializes the charging characteristics accordingly. While charging the battery it monitors the battery status every few seconds in order to switch between stages in time. Before switching to the next stage, it sends a capacity update message to the LC in order to signal the need for an updated charging current

(a) Charging Characteristics of a Li-ion Battery   (b) Charging Characteristics of the Simulated Battery Model
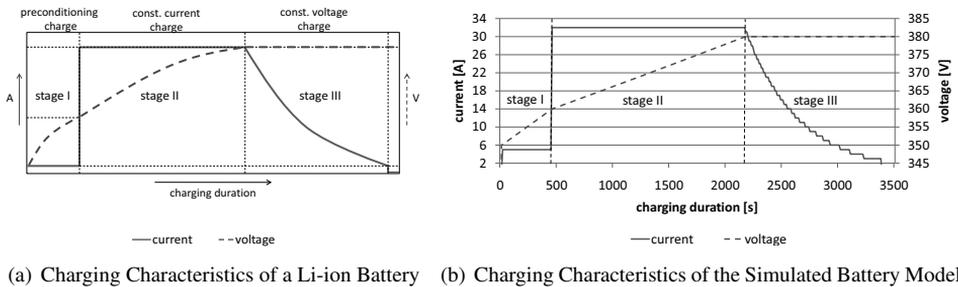
Figure 4: Charging Characteristics of the Battery Model

(see figure 3(b)). Everytime the LC receives charge token request messages or capacity updates from an EV charging in stage 3, the fair load coordination algorithm is triggered and calculates available power capacities for each CP. Afterwards the assigned power capacity is conveyed through update response messages. When receiving the update response message, the charge controller continues the charging process with updated parameters. This behavior can be modeled with the pulse-width modulation signal as specified in [ADI09] for real charge controllers of todays EVs.

The *Load Coordinator* module is parameterized through the totally available power capacity for all connected CPs. In case the LC is located at the transformer of a local substation, it manages the available power capacities for the entire subsegment of this substation. The information regarding the charge request is registered and accessible to the coordination algorithm in the LC.

3   Simulation Scenarios

This paper focuses on two different simulation scenarios for validation purposes of the underlying simulation environment. In the first scenario only one vehicle is charging. This allows for validation of the charge controller, battery and the EVCC behavior. The charging characteristics of the simulated EV are shown in figure 4(b). They conform to the charging progress shown in figure 6(a). In the second scenario three EVs are fast-charging with 22 kVA in a parking area with a limited power capacity of 44kVA. Hence the parking area can only provide enough capacity for fast-charging two vehicles at the same time. Figure 5(a) illustrates the simulation scenario. The EVs start their charging process at 0, 5 and 10 minutes simulation time with a battery capacity each of 22kWh and different *States of Charge (SoC)* at the beginning of each charge process. Figure 5(b) shows the charge current allocation over time for all three EVs in this scenario. These results correspond to similar observations in [KWCL09].

When the third vehicle starts charging with the pre-conditioning charge, the LC has to coordinate the charging process of all three vehicles and has to assign less power capacities to EV1 and EV2 and therefore sends out charge updates. Marker (1) indicates this point
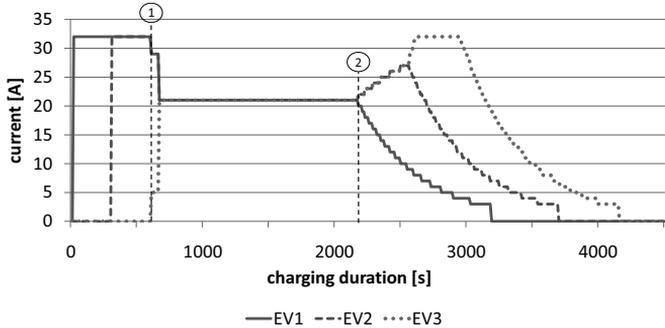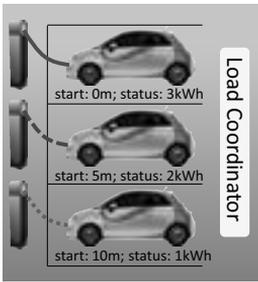
(a) Fast-Charge Scenario

(b) Current Allocation in a Fast-Charge LC Scenario

Figure 5: Fast-Charge Scenario with Load Coordination

in time in figure 5(b) and 6(b). The gradients of the charging progress graphs for EV1 and EV2 decrease accordingly as shown in figure 6(b). After the pre-conditioning charge of EV3, where the maximum current is 5A, all EVs charge with a maximum of 21A in order to satisfy the fair load balancing algorithm of the LC. At position (2) the charge controller of EV1 switches to stage 3. The deallocated power capacity from EV1 can now be equitably allocated to EV2 and EV3. Hence the gradients of the charge progress graphs from EV2 and EV3 in figure 6(b) increase slightly before the graphs saturate due to switching to stage 3 for themselves.
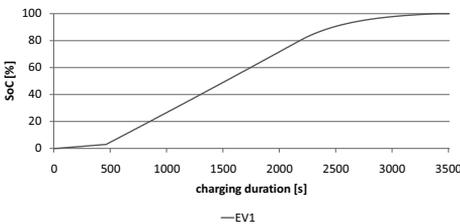
(a) Charging Progress of a Single EV
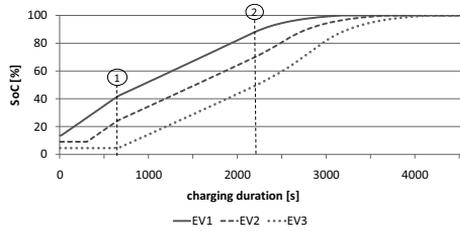
(b) Charging Progress of Three EVs

Figure 6: Charging Progress for both Scenarios

4 Conclusions and Outlook

This paper presents ongoing research for a simulation environment that combines aspects of ICT and power engineering for coordinating available power capacities in case of recharging EVs. The simulation environment incorporates near realistic and adaptable models of lithium ion batteries and charge controllers as traffic generators for the load

coordination communication protocol. Through the application of two manageable scenarios the correct behavior of the simulation models and the load coordination protocol was validated.

Future work will consider Powerline Communications on layer 1 and 2 of the simulation environment. Immediate next steps include scalability investigations and the research of alternative and extended load coordination algorithms. The simulation environment also allows for integration of realistic GEO-based mobility patterns which corresponds to the investigation of large scale scenarios.

5 Acknowledgement

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