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Implementation of a real time capable, flexible and accurate Electric Vehicle model to holistically evaluate Charging Services and Methods

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Abstract

This contribution describes the implementation of a real time capable, flexible and accurate Electric Vehicle model to evaluate charging services and methods in large scale applications. Based on fully transient measurements of the charging process of electric vehicles a model building method has been developed and applied. This modelling approach bases on the parameterization of different phases of the charging process which then is fed into an electric vehicle charging behavior model which can be executed in real time.

The proposed modelling method is described in detail and validated against real measurements and charging behavior showing that the taken approach provides a valuable and flexible model for the emulation and simulation of the charging process of electric vehicles.

Keywords: electric vehicle charging; real time; modelling; electric grid integration; simulation; emulation

1. Introduction

In the near future the energy system and the mobility system will be seen as one system rather than as currently as two individual. This will be emphasized by heavy synergies between the mobility system and the energy system of today. Electric Mobility will be a major part of tomorrow's transportation systems. In order to be capable to reach goals like the 2 °C climate goal it is expected that by 2030 in Europe 60 % of all sold vehicles have a battery that can be charged via the electric grid [1]. This includes full battery vehicles (BEV) as well as plug in hybrid vehicles (PHEV). This expected rise in the penetration of electric vehicles at the same time results in a large amount of electric loads (vehicles that are being charged) that increase the total load on electric distribution systems significantly. Depending on the grid operator, currently a household is planned with a maximum load of approx. 4 kW for low voltage grid level planning. In the medium voltage level, planning a household is mostly even only planned as 500 W. Given that today's EVs are charging at a power rate of 3-22 kW it is clear that high EV penetration scenarios hold novel challenges to the electric distribution grids. As, from a resource perspective, it is not feasible to simply expand all electric distribution grids in such a way that the expected power requirements caused by the higher loads of the future can be transmitted, smarter approaches are required. Different algorithms and communication means are implemented into charging infrastructure to reduce the peak load on the one hand and implement grid supporting functions on the other.

Electric grids are critical infrastructure for today's energy hungry society, their operation is naturally expected. To directly implement novel methods and approaches without a reliable test prior to the installation is clearly not possible. Building up large scale hardware environments that enable such tests with real hardware also is no real option due to the massive costs implied. A mixture of software simulation and hardware in the loop tests is the best way to test novel approaches and methods for high EV penetration scenarios. This combines the required accuracy with a reasonable cost factor. The biggest drawback of a simulation always is the model itself.

The objective of this work is to develop a flexible EV-charging-model that is able to accurately simulate the charging behavior of different commercial EVs while connected to an AC power supply. The main motivation behind this goal is the following: In order to investigate grid integration of electric vehicles in any penetration- and smart-charging-scenarios, simulations are an excellent choice to evaluate all relevant impacts of collective EV charging on the grid. Being able to dynamically simulate the charging behavior of commercial EVs enables a wide range of possible experiments if the developed EV-model is embedded in a larger, holistic electric grid simulation. Furthermore, the ability to generate the EV-charging-behavior of commercial or artificial EVs for various other experiments at any time seems to be of great benefit.

Several other studies on EV load modelling have already been carried out ([2]-[4]), many of which use a constant load model to simulate EV charging. However, none of mentioned studies concentrates on exactly reproducing the characteristic peculiarities in the charging behavior of different commercial EVs. It is dependent on many factors, especially on the internal charging control algorithms of the vehicle. Therefore, other approaches to reach this goal are followed in this work.

Today, most electric vehicles are equipped with Li-ion batteries. Therefore, this battery type was chosen for the battery model. Fig. 1 shows the theoretical charging behavior of an exemplary Li-ion battery. At the beginning, as long as the state of charge (SoC) is lower than roughly 10 %, the charging current stays low to avoid battery damage. But after that, the charging current rises to the maximum possible value and stays constant for a long time ("constant current phase", CC), while the battery voltage is increasing. As soon as the battery voltage reaches its cell-limit, the charging-controller of the battery goes into another state, which can be called "constant voltage phase" (CV). In this phase, the charging current exponentially decreases while the battery voltage stays constant until the battery is fully charged.

The latter two phases are dominant in everyday-average EV charging scenarios. This assumption can be done as EV manufacturers usually do not allow the EV user to discharge the battery to a state that could shorten its lifetime or possibly damage its cells. Therefore, the focus for the EV-charging-model is placed on the constant current and the constant voltage phase of the charging. However, it should be noted that the aim of this work is not the development of a precise battery model supporting cell-voltage calculations (as performed in [6] and [7]). Nevertheless, future combinations of this work with these battery models are considered as well during the software design.

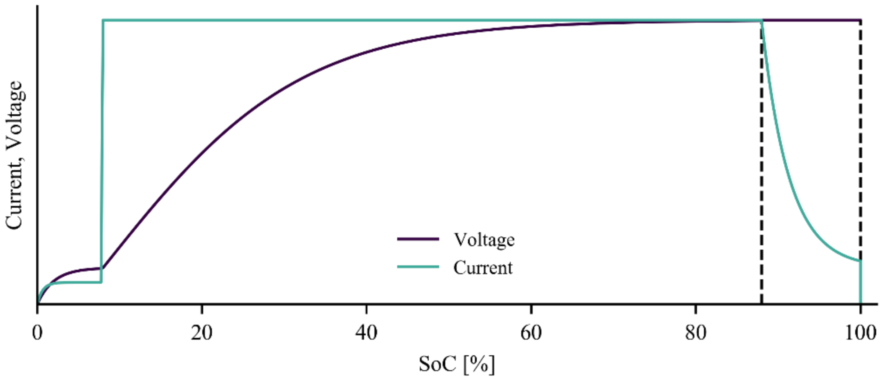

Fig. 1 Theoretical charging behavior of a Li-ion battery [7]

2. Methodology

2.1. Measurements

As a first step towards the development of an accurate simulation model of electric vehicle charging behavior, a highly accurate measurement of the charging process of real EVs is necessary to identify all relevant characteristics. Therefore, comprehensive measurements were performed with several electric vehicles.
Charging was done with a 25 kW AC electric vehicle supply equipment (EVSE) that is compliant with the state of the art EV-conducted-charging-standard IEC 61851. [5]

In accordance with IEC 61851, the EVSE allows controlling the charging process by sending a pulse width modulation signal via the control pilot (CP) of the charging cable. It defines the maximum allowed charging current (PWM-current) for the EV. Furthermore, it can start and stop the charging process by enabling or disabling the PWM signal in the charging cable. In this work, this signal is called enable-flag.

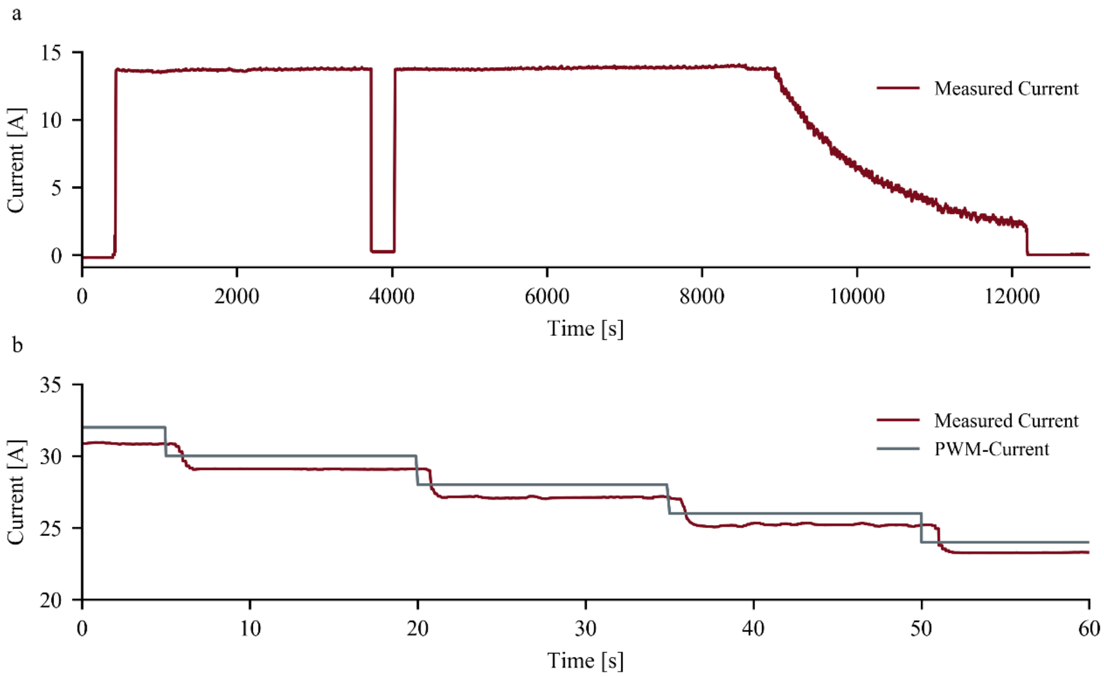

Fig. 2 (a) Charging Curve of a single phase EV (EV1); (b) EV Reaction delay of EV2

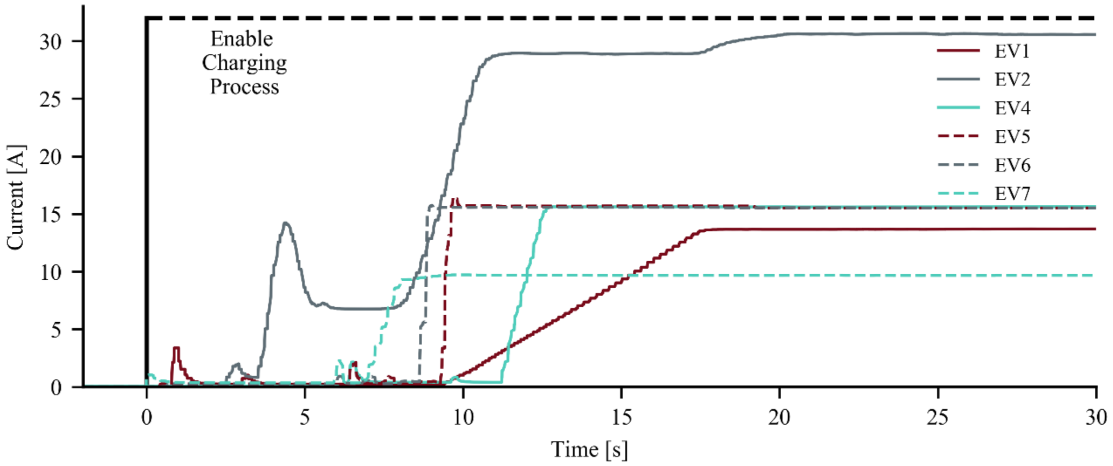

Fig. 3 Charging initialisation phases of different EVs

Fig. 2 (a) shows the measured charging current of a typical EV. The constant current phase and the constant voltage phase at the end of the charging process are clearly visible. The reason for the drop in the charging curve during the cc-phase is assumed to be an internal cooldown process of the EV-battery, but this is not perfectly clear.

Furthermore, the EV-currents of all measured cars showed a reaction delay up to 1.5 seconds after the PWM-current changes, as can be seen in Fig. 2 (b). According to IEC 61851, this delay must be smaller than 5 s, which has held true for all measured EVs. This behavior must also be taken into account for the EV simulator.

Fig. 3 shows the charging initialization phase of different EVs (in accordance with the nomenclature of this paper). For all EVs displayed in Fig. 3, the charging process was triggered with the enable-flag switching from off to on. One can see that the curves distinctly differ from each other. This initialization behavior – although lasting only up to approximately 20 s – must also be covered in the EV simulation in order to get precise simulation results. This is especially of use as the EV model is also needed for the simulation of cold load pick up scenarios.

2.2. Pre-Analysis and Parameterization

In the previous section the most important characteristics of the charging behavior of real commercial EVs are discussed. Taking these EV measurements, a parameterized EV simulation model can be developed by analyzing each phase on its own and calculating characteristic parameters. In Fig. 4, the approach for this work is illustrated. The actual simulation can only be executed after parameters are collected and calculated in the pre-analysis. This step only has to be performed once for adding new EVs to the simulation. After manually analyzing the measurement curve and configuring the first parameters, the rest of the pre-analysis is iteratively performed by an individual tool. As soon as the EV parameters are determined, the EV simulation is ready to be started.

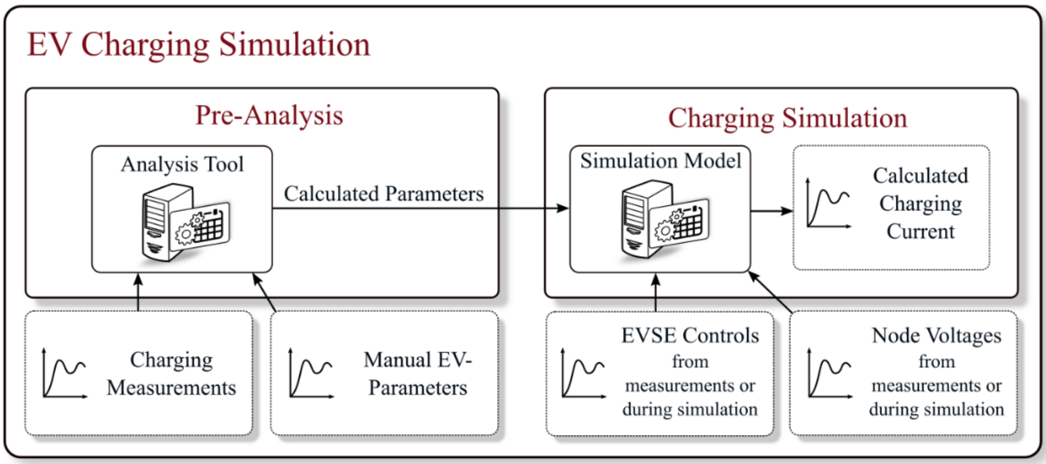

Fig. 4 EV Simulation Model

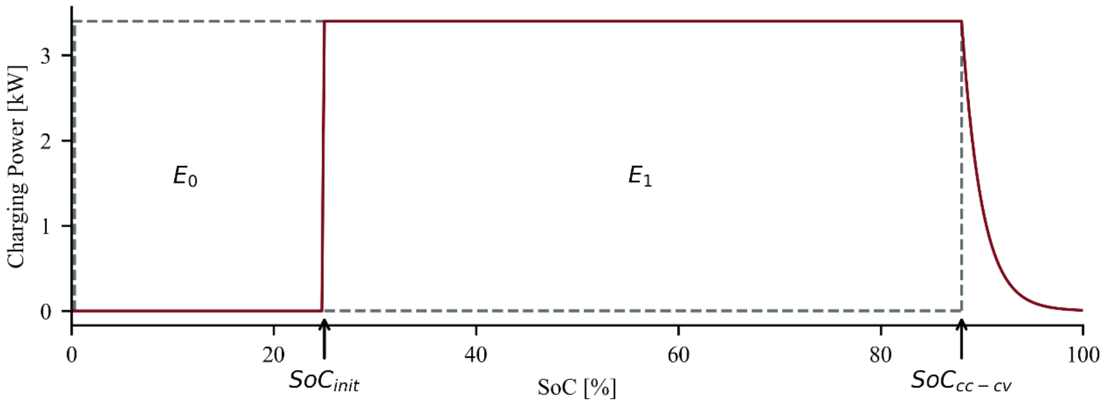

Fig. 5 Energy and SoC calculation

It is also possible to create generic EV parameters and thereby construct a custom EV that has nothing in common with commercial EVs. In this way, the pre-analysis can be skipped as there is no measurement to analyze.
A detailed description of each phase of the pre-analysis is found in the following subsections. After that, the approach for the EV simulation state model will be explained in section 2.3.

2.2.1. Energy- and SoC-Calculation

In order to make the simulation independent from the measurement time, the state of charge (SoC) of the battery is defined as the main control variable of the simulation. Especially the change from the constant current phase of charging to the constant voltage phase is SoC-dependent. Evaluating at which SoC this happens is the main goal for this part of the pre-analysis. The second (less important) objective is to calculate the initial SoC which the EV had at the beginning of the charging process. This is only needed for comparison between measurement and simulation, as can be seen in chapter 3.

The critical SoC calculations are performed as follows:

$$SoC_{init} = \frac{E_0}{capacity} * 100 \tag{1}$$

$$SoC_{cc-cv} = \frac{(E_0 + E_1)}{capacity} * 100 \tag{2}$$

Fig. 5 shows the used variables and characteristics for the SoC calculations in the equations (1) and (2). Most of the time, the EV battery is not completely empty at the beginning of the charging process (This was also the case in the performed measurements). Thus, the exemplary charging process in Fig. 5 starts with a SoC larger than 20 percent. For the calculation of the initial state of charge (SoC_{init}), the energy E_0 (i.e. the energy which is already in the battery before the charging starts) is put in relation to the total battery capacity. For SoC_{cc-cv}, a similar operation is performed with the sum $E_0 + E_1$.
In order to calculate E_0 and E_1, the charged energy must be iteratively calculated by numerical integration. E_1 can only be found if the measurement-time of the cc-cv-change is manually localized and then used in the iterative energy calculation to cut off the constant voltage phase of charging from the rest of the charged energy.
This exact approach is needed because real EV charging behavior (e.g. shown in Fig. 2 (a)) often differs from this theoretical characteristics, even during the simple constant current phase.
After calculating SoC_{cc-cv}, the value is saved to the EV parameters and can be used in the simulation.
It should be kept in mind that the accuracy of the calculated SoCs is dependent on the accuracy of the used battery-capacity value. Picking the EV-battery-capacity from the published datasheets is not sufficient to get a precise result, especially as not all batteries are configured to completely charge from a SoC of 0 to 100 percent.

2.2.2. Charging-Initialization Phase

In Fig. 3 the different initialization behavior of measured EVs is shown. In order to replicate these curves within an arbitrary simulation scenario, a linear approximation of significant peeks, valleys and slopes of the measurement-curve is performed. The elapsed seconds and the corresponding current of the picked values are stored in the EV parameters. If the EV is a three-phase EV instead of a single-phase EV, the same initialization behavior can either be copied for phase L2 and L3, or each phase uses its own parameters.

It should be noted that the charging initialization phase is not related to battery charging at very low states of charge. The behavior at very low SoC percentages has not been investigated.

Some EVs additionally show a similar behavior to the initialization phase after the PWM-current increases. To parameterize this as well, the same linear approximation method is chosen.

2.2.3. Constant Current Phase

In the constant current phase, the EV mainly retraces the PWM-current signal which is sent from the EVSE. However, there are two special characteristics all cars have showed during the measurements:
First, the EVs do not exactly apply the maximum charging current the EVSE sends. Instead, the measured current is always a certain percentage lower (dependent on the EV) than the PWM-current. This is taken into account and written to the EV parameters. In most cases, the deviation in the measurements has amounted roughly to 10% of the PWM-current.
Second, each EV has an internal maximum current for its mains leads. If the PWM-current is too high, only the maximum current of the EV will be charged. This EV-specific maximum current is also written to the simulation parameters.

2.2.4. Constant Voltage Phase

The constant voltage phase of charging, where the current exponentially drops (independent from the PWM-current), needs more intense calculation to be parameterized. The idea is that fitting the current-measurement with an exponential function returns parameters that can be used within the EV simulation for simulating the CV-phase. The function which should be parameterized is

$$f(x) = A\ e^{-B*x} + C, \tag{3}$$

where $x = (SoC - SoC_{cc\text{-}cv})$ and A, B and C are the parameters to be determined by a nonlinear regression analysis, i.e. a curve fit. For the regression analysis, the Levenberg-Marquardt algorithm for solving nonlinear least-squares problems was chosen. The calculated parameters A, B and C are written to the EV parameters for the simulation. However, there are cars which have not shown any constant voltage phase during measurement (probably due to

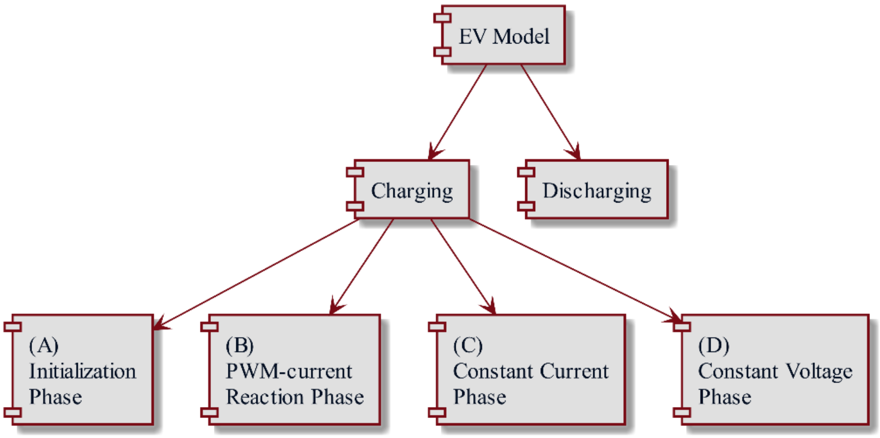

Fig. 6 States of the EV Simulation

an internal configuration that prevents the battery to be fully charged). In these cases, no CV-parameters are calculated.

2.3. Charging Behavior Simulation

As soon as the EV simulation parameters are determined (see section 2.2), the simulation can be performed. It is implemented as a state model that dynamically chooses in which charging phase the simulation is situated – depending on the state of charge and the elapsed simulation time. Fig. 6 shows all states of the simulation that can be active. They correspond to the identified phases in sections 2.1 and 2.2.

Assuming that the simulation is in “charging” state, there are four different sub-states only one of which can be active. Their activation-conditions and further descriptions are:

A. Initialization Phase: Each time when the EVSE enable-flag (described in section 2.2.2) turns from off to on, a timer is set to zero and the initialization phase takes place. As long as this timer-value is smaller than the (fixed) duration of the EV-specific initialization phase, the phase is active.
B. PWM-current Reaction Phase: Each time when the EVSE “PWM-current” (also described in section 2.2.2) increases, a timer is set to zero and this phase is activated. It stays active as long as the timer-value is smaller than the (fixed) duration of the EV-specific PWM-current reaction phase.
C. Constant Current Phase: This phase is active if phases A and B are inactive and the SoC is smaller than $SoC_{cc\text{-}cv}$.
D. Constant Voltage Phase: This phase is active if phases A and B are inactive and the SoC is larger than $SoC_{cc\text{-}cv}$. As soon as the SoC reaches 100 %, the charging current is always set to 0 Ampere.

Furthermore, each phase always checks if the PWM-current is lower than its calculated current. If this is the case, then the current is determined by the constant current phase (see C).
The EVSE control values which the EV model needs can be changed either before a simulation-step or only when required. Thus, the simulation can dynamically respond to control-changes that come from external sources (for example other simulators or connected hardware in the loop). As pointed out in Fig. 4, the charging simulation also takes into account varying mains voltages during the simulation.

2.3.1. Battery Model

The battery model has two class attributes, namely its current SoC and its fixed battery capacity. The battery SoC is updated at every iteration step of the simulation by passing an energy value to it, which can be either positive (charging) or negative (discharging). After that, the battery model updates its SoC:

$$SoC_{new} = SoC_{old} + \frac{energy\_increment}{battery\_capacity} * 100 \tag{4}$$

Due to the design of the entire simulation model, the battery model can be exchanged at will if a more sophisticated model is required.

2.3.2. Reaction Delays

Reaction delays, as pointed out in section 2.1, are also addressed. The current-measurement-curve of each EV is compared to the set PWM-current during rising or declining steps (Fig. 2 b). Then, the average EV reaction delay after PWM-current-changes is written to the EV parameters. The simulation makes use of this EV-specific reaction delay.

3. Results

In this chapter, various simulation results and comparisons with the EV measurements are presented. In order to test the simulated EV reaction behavior as well, the PWM-current was frequently changed at some parts of the measurement. The following sections present selected simulation results for several commercial EVs.

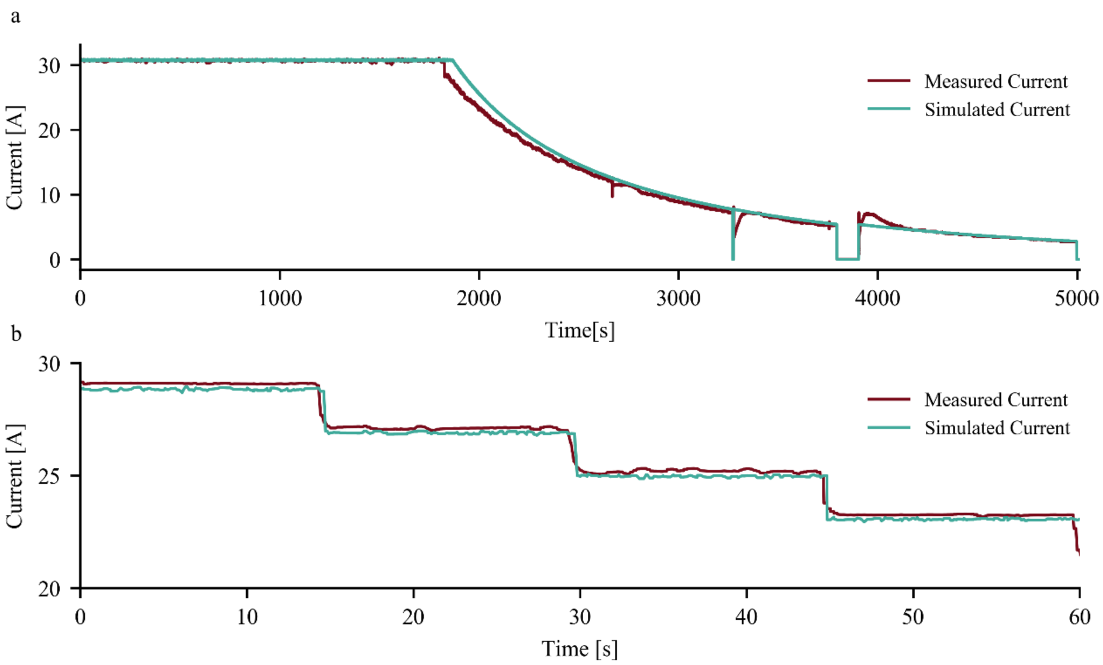

Fig. 7 (a) Simulated current (of EV2) in comparison to the measurement (using the same EVSE-set values); (b) Other part of (a) showing PWM-current-steps

3.1. Comparison with Measurements

Fig. 7 shows the simulated EV charging process in comparison to the measurement of the real charging process. The EVSE control values (i.e. the PWM-current and the enable-flag) which are used in this simulation-scenario are the same like those from the measurement. In this way, a direct comparison is possible. One can clearly see that in most parts of the plot, the simulated current is located very close to the measurement.

All the important charging-characteristics like the CC-phase, the CV-phase (Fig. 7 a) and the reaction to changes in PWM-current (Fig. 7 b) are precisely simulated. The current-drop during the CV-phase in Fig. 7 a happens due to a turned off enable-flag and therefore can be simulated. A customizable fake noise signal is also added to the simulated current in this case. The relative deviation between the simulation and the measurement amounts to 2.48 %.

The EV simulation also supports three phase EVs with an individual charging behavior for each separate phase, as can be seen in Fig. 8 for the charging initialisation phase. For this specific EV the currents of the three phases look similar but are shifted in time.

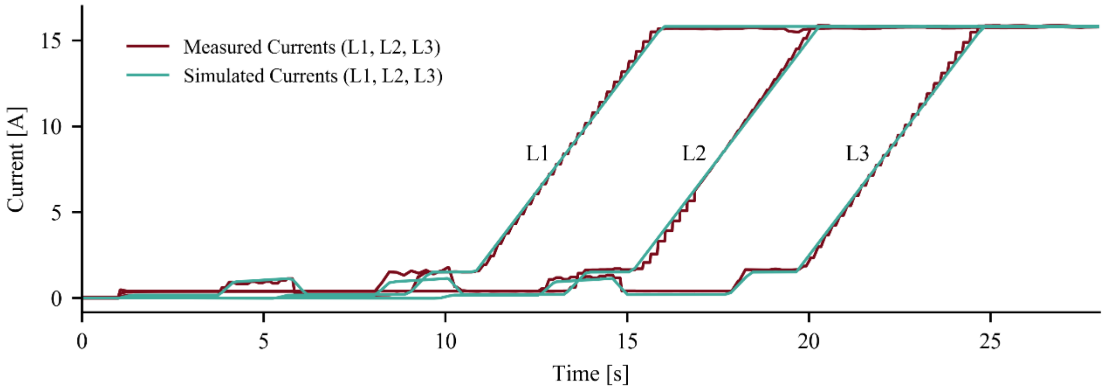

Fig. 8 Simulated Initialization-Phase of a three phase EV (EV3) in comparison to the measurement

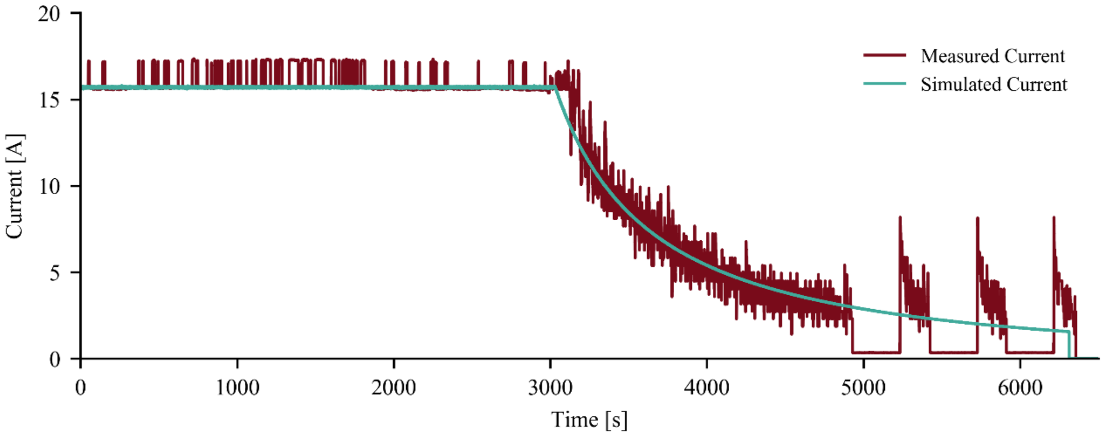

Fig. 9 Simulation in comparison to new measurement data

The simulation in Fig. 7 reads EVSE control values from the same measurement which was used to parameterize the model, whereas the presented EV in Fig. 9 was measured twice: The first time to paramaterize the model, and a second time with a differing initial state of charge. In the case of Fig. 9, the EVSE control values from the new measurement are used to generate the simulated current to allow direct comparison between the simulation and the new measurement.
In fact, the EV from the second measurement was not even identical with the EV from the first measurement (but still of the same brand and type). As can be seen in the figure, the measured current has very high noise. It also shows a fluctuating charging behavior at the end of the charging process, which is not covered by the EV simulation. The relative deviation between the simulation and the measurement amounts to 7.57 %.

3.2. Embedded Scenarios

As already mentioned, the main motivation behind this work is the use of the EV charging simulation in large scale co-simulations to investigate the future grid integration of electric vehicles. For example, an anticipated distribution scenario of different commercial EVs (according to EV sales statistics) can be simulated in any arbitrary grid up to the sub-second timescale. It is also planned to simulate driving scenarios in which the EVs connect to and disconnect from charging stations at different grid nodes. Further results on this topic will be presented in future work.

4. Discussion

Results show that the developed EV charging simulation is capable of precisely modelling the charging behavior of commercial electric vehicles. Comparisons between the simulation and the corresponding measurements result in relative deviations of only 2.48 % for the EV in Fig. 7 or 7.57 % for the EV in Fig. 9. The larger deviation for the latter EV is based on the massive noise the EV had during the measurement (It is presumed that some internal electric EV components were malfunctioning during the measurement). However, when visually comparing the curves in Fig. 9, one can see that the simulation is highly accurate. Generally speaking, the deviations mainly occur due to the noise-differences between the simulation and the measurement.

One major advantage of the EV simulation is the ability to use it in real-time within a larger co-simulation for various purposes. For example, hundrets of EV simulator instances can be created and used to test their collective power load in a large electricity grid. Differences in grid impacts between various commercial EVs can be investigated. Additionally, the model can also be utilized to control an RLC-load by an EV emulator which was developed at AIT. In this way, charging infrastructure can be precisely tested without the need for real vehicles.

EV-specific characteristics like reaction delays, initialization phases of the charging-process, and generated noise signals are implemented in the model. Furthermore, three phase EVs are supported as well.

Combined with the real time functionality, this EV charging simulation can precisely reflect large parts of real charging behavior and be used in many other projects.

However, there are also some limitations in the simulation. Sometimes, unpredictable peaks or charging pauses occur during real measurements. These are not implemented in the model. However, this limitation is no major drawback as it happens quite rare (depending on the measured EV type).
The EV simulation is not based on a physical or mathematical battery model, but on the principle called "simulation by observation". Hence, there exist some limitations, e.g. in implementing modelled temperature dependencies or battery degradation in the simulation. Nevertheless, there are other simple measures to implement these characteristics, e.g. by observing real measurements and parameterizing various dependencies.
As already mentioned earlier, one major difficulty of the pre-analysis is defining the correct (i.e. in reality utilized) battery capacity for the simulated EV. Even if it is extracted from the EV-datasheet, it is not 100 percent safe that the whole capacity range is actually used during a full charging process. It is clear that an erroneous battery capacity also leads to erroneous calculations of the states of charge, as can be seen in equations (1), (2) and (4).
One solution approach for this issue would be to completely discharge the EV battery and fully recharge it in the laboratory while measuring the charging power and current. By using a slightly modified version of the analysis-process described in section 2.2.1, the total charged energy could be calculated, which is the desired EV battery capacity in this case.

5. Conclusion

The objective of developing a flexible electric vehicle charging simulation was successfully fulfilled in this work. The implemented solution has very low deviations from real measurements and can additionally be used to create any fictional customized EV charging behavior.
Furthermore, the EV charging simulation can be embedded in larger co-simulations. These co-simulations could, for example, investigate in grid integration of electric mobility by simulating and controlling hundreds of different EVs in a large grid.

Future work will implement such scenarios by connecting the EV charging simulation to other components like simulated charging stations (EVSEs), mobility controllers and professional grid simulations. A connection with real hardware in the loop (e.g. emulated EVs or real EVs) is planned as well.
By embedding the EV charging simulation in larger test environments, the effects of different future EV charging services and methods will be evaluated in a resolution up to the sub-second-timescale.

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