# Charging Demonstrator for Ancillary Service Provision in Smart Grids

Kai Zhang[1*], Dante Recalde[1†], Tobias Massier [1‡], Thomas Hamacher [2§]
[1]TUM CREATE Limited, #10-02 CREATE Tower, Singapore 138602
[2]Technical University Munich, 80333 Munich, Germany
Email: *kai.zhang@tum-create.edu.sg, †dante.melo@tum-create.edu.sg, ‡tobias.massier@tum-create.edu.sg
§thomas.hamacher@tum.de

***Abstract*—The target of this paper is to provide a charging infrastructure design for a carpark scenario which enables demand response (DR) management. The presented system not only allows an optimal charging scheduling to maximize the revenue for the carpark operator, but also enables the participation in DR. Numerous advantages to deploy a smart power sharing charging infrastructure in the future carparks have been discussed in the literature. A smart charging scheduling strategy leads to a better usage of grid power and improves the grid stability. Moreover it benefits the users to charge their own electric vehicle (EV) with lower cost and generates additional revenues for carpark operators. The utilization efficiency of the charging station will also be improved in the meantime.**

***Index Terms*—Demand Response, Electric Vehicles, Charging Infrastructure, Carpark**

## I. Introduction

With the increasing demand of sustainable development and greenhouse gas emissions reduction in the transport sector, EV technology provides a cleaner option than conventional vehicles. Studies have shown that in cities like Singapore where natural gas plays a major role in power generation, the polluting emissions as well as greenhouse gas emissions could be reduced by introducing electric vehicles into the market. As the number of EVs increases, development of a better charging infrastructure plays an important part. Better charging infrastructure not only means the optimization of the charging process for each individual EV but also to see the EVs and electric vehicle supply equipment (EVSE) as an active part of the power grid and to optimize the charging based on the grid state. For example, when a power shortage occurs, the charging station may reschedule or even turn off the charging process to reduce the impact on the grid. If the charging demand is high in a carpark charging station, the carpark operator may schedule the charging in a way that the maximal power capacity of the carpark is not exceeded.

Smart charging of EVs and power sharing has been discussed in the literature from different aspects. In [1] and [2], a safety design of remote EV charging, monitoring and management system is implemented. The authors of [3] propose a master-slave architecture to improve the response time of the existing system in [1]. These works concentrate on the hardware design and introduce a power-sharing charging system, where several EVs are able to be charged with variable current from one circuit. However the multiplexing control method proposed in the works does not take into account of the energy market from the operational perspective of the carpark. Since the carpark operator is a potential demand response aggregator, the impact of smart charging scheme for EV in a Singaporean carpark as well as the potential benefits that the carpark operators could receive by deployment of DR programs are studied in [4]. It shows that additional revenue can be generated for the carpark operators with deployment of such smart charging infrastructure. The authors of [5] propose a charging strategy to minimize the charging price for the customers. Work [6] considers the carpark as a flexible load participator in their load aggregation model and overall cost minimization is proposed. The authors in [7] propose a smart carpark charging infrastructure with renewable generations and utility grid connectivity involved. However, none of these works provide the requirement for a carpark charging infrastructure design with demand response.

In this work, a charging infrastructure design with a smart charging algorithm taking into account of minimizing the charging cost for the customer as well as maximizing the revenue generated for the carpark operators is presented. The communication between EV and EVSE plays an important role in enabling DR management. The controller design in this work is compliant to IEC 61851 and the pilot function is implemented utilizing pulse-width modulation (PWM) through a control pilot (CP) circuit. It addresses the software and hardware requirements for such a system. The paper is organized as follows. An overview of the demonstration system is given in Section II. The hardware design for generating, amplifying and pre-processing the pilot signal is introduced in Section III. The high-level controller to solve the optimal charging scheduling problem and the user interface introduced in Section IV. Section V presents the test results for the scheduling algorithm and the hardware compliance.

## II. System Overview

In this section, we introduce the concept of the charging demonstrator for multiple vehicles and its system architecture. Fig. 1 shows the conceptual carpark charging station with multiple EVs connected to EVSEs. The assembled demon-

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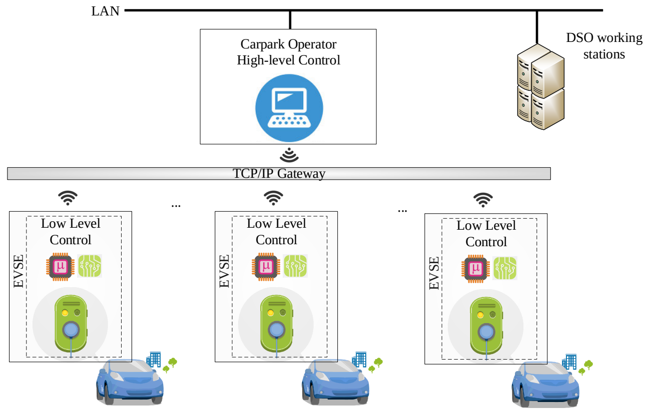


Fig. 1. Demonstration system concept

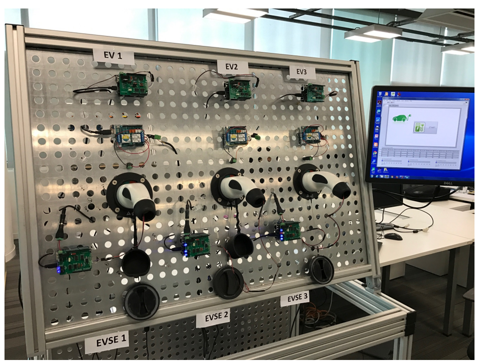


Fig. 2. Demonstrator

stration system is shown in Fig. 2. The demonstration system comprises two levels.

- The EVSE serves as a low-level controller. It detects the EV status by monitoring the pilot signal, collects local information like meter reading, EV status and controls the charging process. It also contains a Transmission Control Protocol/Internet Protocol (TCP/IP) server, providing local information as inputs for the charging scheduling algorithm. EVSE connects with EV through an IEC 62196 Type 2 connector. In the demonstration system, EV simulators are implemented to simulate the behavior of EV during the charing process specified by IEC 61851. It uses the state machine model and can be controlled and monitored on its interface.
- The high-level controller solves the optimal charging scheduling problem and sends control actions to the low-level controller via wireless connections. It also features a communication interface to the distribution system operator (DSO) to enable the participation in DR. Any incidents during the charging process, like the status change of the vehicles, flexible load interruption request from DSO or the update of the price information will enable the system to reschedule the charging process. The beforehand defined charging current is calculated by the algorithm at the high-level controller, taking into account of the customer-preferred charging mode, the energy price prediction information and charging parameters.

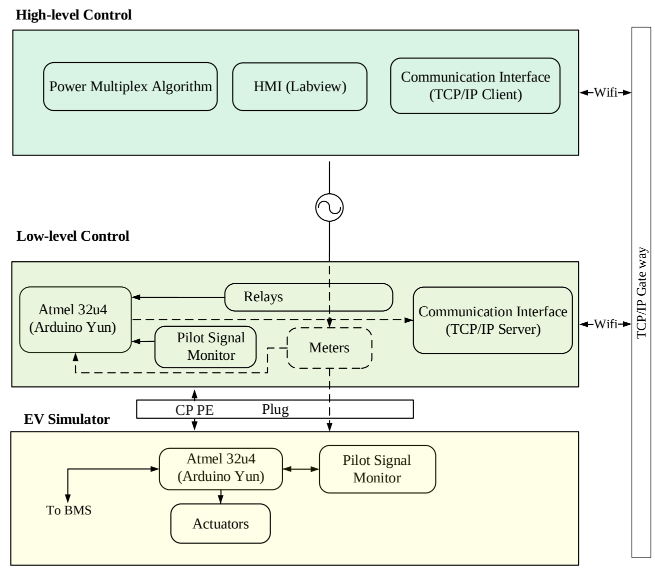


Fig. 3. Two-level controller

In Fig. 3, the two-level control system is illustrated. The system is is implemented in a scalable way that additional EVSEs and EVs can be added to the existing system easily.

## III. Low-level Controller

### A. EVSE signal generator and monitor

The EVSE signal generator uses a non-inverting amplifier to amplify the 5 V/GND input to $\pm 12$ V output PWM signals. The CP signal monitor should acquire the voltage level information and it consists of two inverting operational amplifiers. Since the 12 V input signal is beyond the measurable range of the microcontroller, the gain factor for the first amplifier is set 1/3. The second inverter is implemented as a low pass filter (LPF) to filter the average value of the PWM signal, which can be used as transition condition for our EVSE state machine model. The cut-off frequency for LPF is 125 kHz, which is sufficient to average the 1 kHz PWM signal. Fig. 4 presents the circuit schematic.

The EVSE firmware is implemented in C++ using the Arduino integrated development environment (IDE). The core of the software is the EVSE state machine model presented in Fig. 6. It detects the correct vehicle status based on the CP signal measurement. The EVSE state machine model is derived based on the control pilot state machine model specified by IEC 61851.

### B. EV simulator signal monitor

The signal monitor of the EV simulator measures the voltage level as well as the PWM signal duty cycle. It consists of three operational amplifier and one comparator. Two inverting amplifiers work in a similar manner as the LPF in EVSE signal monitor. The amplifier and comparator circuit is to generate

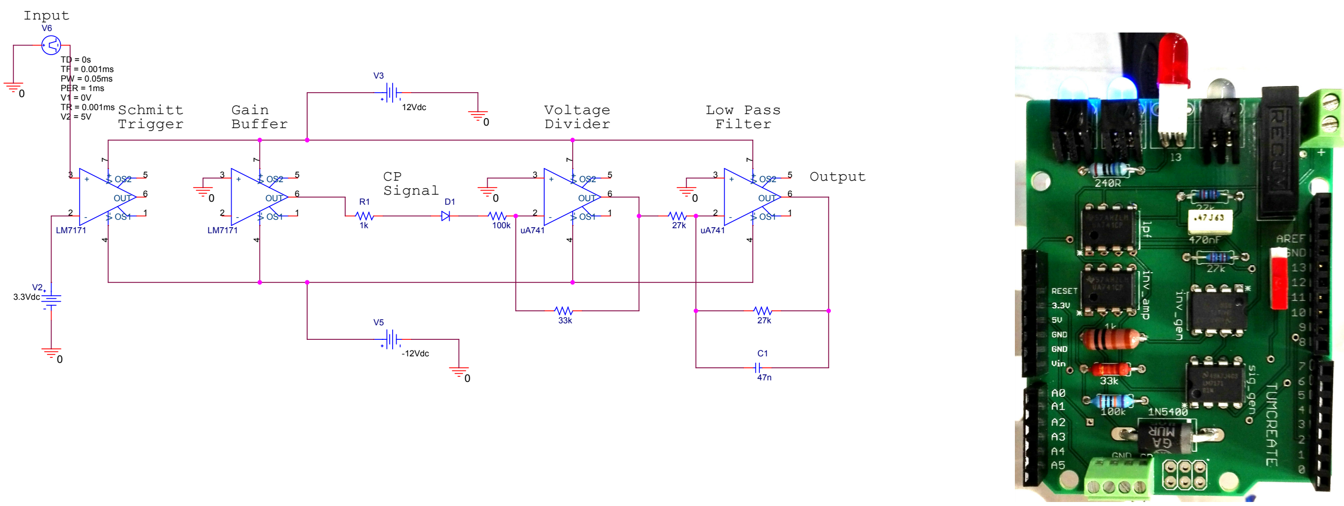


Fig. 4. EVSE signal generator and signal monitor (left: schematic right: PCB)

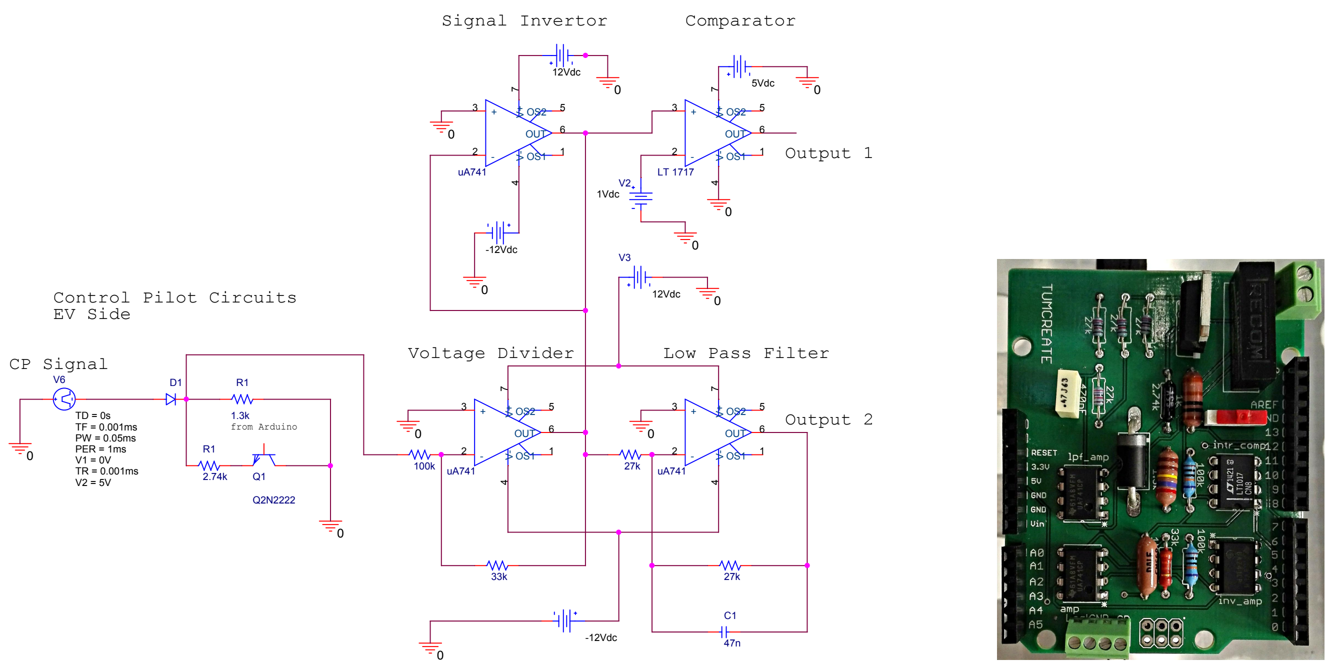


Fig. 5. EV signal monitor (left: schematic right: PCB)

a 5 V interrupt signal for the pulse width measurement which is used for the charge current calculation. Fig. 5 presents the circuit schematic. In fact the DC output signal of the LPF is correlated in a linear way to the charge current and hence can be used for the calculation. We combined the LPF output signal with the interrupts signal to have a robust pilot signal detection. The EV simulator firmware is implemented in a similar manner as the EVSE controller. It also contains a state machine model designed to interact with the EVSE.

## IV. High-Level Controller

The high-level controller consists of communication interface to low-level controller, data synchronization unit, user interface and power scheduling algorithm. Due to different processing time at the low level controller and communication delay, the high-level controller has a different data updating rate for each low-level controller. It is handled by a data synchronization unit which utilizes a time window to associate the data to archive the same data updating rate. The communication between two levels is followed by a predefined cURL command in the format of

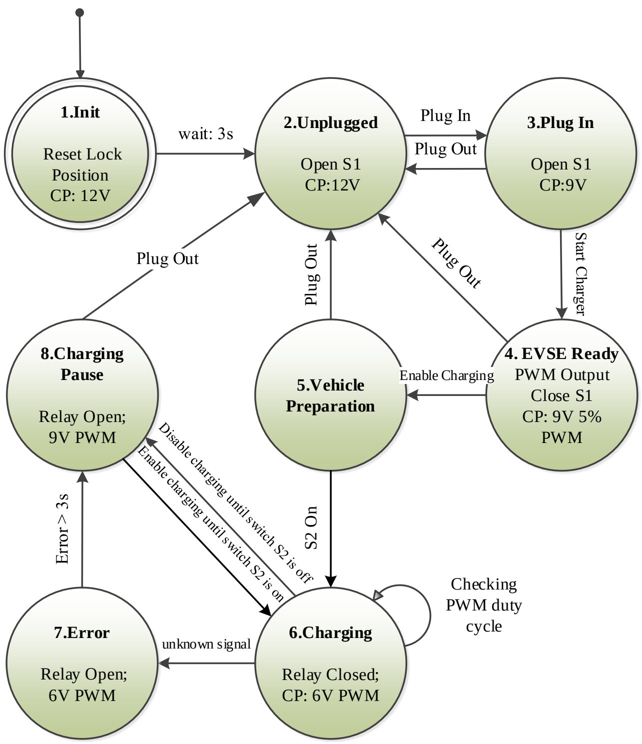


Fig. 6. EVSE state machine model

***http://[Controller IP Adress]/[Action]/[Value]***. For example, ***http://192.168.0.1/cc/20*** is utilized to set the charge current to 20 A at the given EVSE. The user interface is designed for the interaction between the user and the system. It is used to validate the user's identity and to configure the charging parameters. The price data which are required for solving the optimal charging scheduling problem are updated from the Energy Market Company (EMC) in Singapore. It includes the energy price forecast information for 2 days in a half-hour interval.

### *A. Charging parameters*

Based on the customers' willingness to take part in provision of ancillary services, two charging options are provided for each customer: economical charging and fast charging. The charging process for the economic charging is scheduled in a way that the overall price for the customer is minimized. Fast charging mode allows the EV to charge with the maximal allowable power. In order to optimize the charging schedule, further information is required:

- Battery capacity in kWh
- Initial SOC (denoted as $x^0_{c,m}$ in the optimization)
- Desired SOC (denoted as $x^{req}_{c,m}$ in the optimization)
- Charging mode (economical charging, fast charging)
- Charging time requirement

These information is necessary to formulate the individual EV constraint in the optimization problem. The charging scheduling algorithm is first formulated in [4], which minimize the total energy cost for the carpark operator in subject to electricity prices, reserve prices, individual EV constrains and carpark power constraints. It generates the maximal revenues for the carpark operator.

### *B. Charging scheduling algorithm for provision of ancillary services*

Let $\Omega^C$ denote the set of EV parking events and $\Omega^M$ the set of market periods. The total charging cost can be minimized by a linear optimization. The goal of this optimization is to find the optimal charging schedule for the EV aggregator considering the energy price and incentives obtained by provision of ancillary services. The optimization problem is formulated as:

$$\min \sum_{c\in\Omega^C}\sum_{m\in\Omega^M}\left[\chi^E_{c,m}+\chi^R_{c,m}\right] \tag{1a}$$

$$u_{c,m}=\left[u^{fix}_{c,m}+u^{flex}_{c,m}\right] \tag{1b}$$

$$\chi^E_{c,m}=u_{c,m}\cdot\Delta t\cdot\mu^E_m \tag{1c}$$

$$\chi^R_{c,m}=-u^{flex}_{c,m}\cdot\Delta t\cdot\mu^R_m \tag{1d}$$

where $u_{c,m}$ is the total charging power for car $c\in\Omega^C$ at period $m\in\Omega^M$. The total charging power is split into two components, $u^{fix}_{c,m}$ represents the fixed charging power and $u^{flex}_{c,m}$ is the flexible charging power that can be re-scheduled to a future time. $\Delta t$ is the time duration of each market period. The energy price is given by $\mu^E_m$ and $\mu^R_m$ depicts the incentive obtained by the EV aggregator. This paper assumes the carpark's participation in DR as interruptible loads. Under this program, load aggregators are scheduled for provision of reserves during contingencies and paid based on the reserve price.

The individual vehicle state of charge (SOC) is modeled using the following equations:

$$x_{c,m+1}=\boldsymbol{A}\cdot x_{c,m}+\boldsymbol{B}\cdot u_{c,m} \tag{2}$$

where coefficients $\boldsymbol{A}$ and $\boldsymbol{B}$ depict the relationship between the inputs and the state of the EV $x_{c,m+1}$ at the next market period.

The following constraints are considered:

$$x^{min}_{c,m}\le x_{c,m}\le x^{max}_{c,m} \qquad \forall c\in\Omega^c,\, m\in\Omega^M \tag{3}$$

$$0\le u_{c,m}\le u^{max}_{c,m} \qquad \forall c\in\Omega^c,\, m\in\Omega^M \tag{4}$$

$$0\le u^{flex}_{c,m}\le u_{c,m} \qquad \forall c\in\Omega^c,\, m\in\Omega^M \tag{5}$$

$$x^0_{c,m}+\sum_{c\in\Omega^C}(u^{fix}_{c,m}+u^{flex}_{c,m})\Delta t \le u^{req}_{c,m} \qquad \forall m\in\Omega^M \tag{6}$$

$$\sum_{m\in\Omega^M}u_{c,m}\le u^P_m \qquad \forall m\in\Omega^M \tag{7}$$

Equation (3) limits the battery SOC based on the user preferences. Equation (7) constrains the total scheduled capacity so that it prevents discharge of the battery back to the grid and limits the maximum charging power based on the EVSE constraints. Equation (8) constrains the amount of flexible

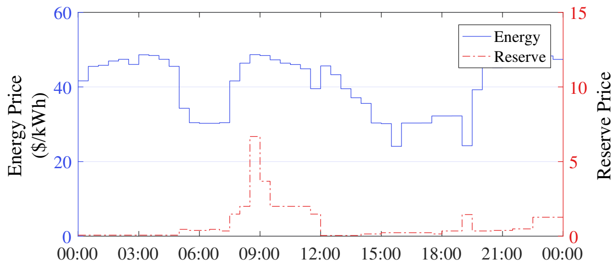


Fig. 7. Energy price and reserve price

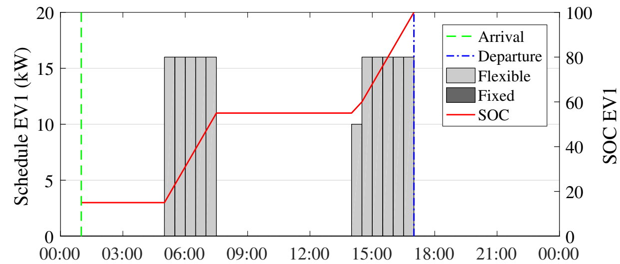


Fig. 8. Charging schedule for EV1

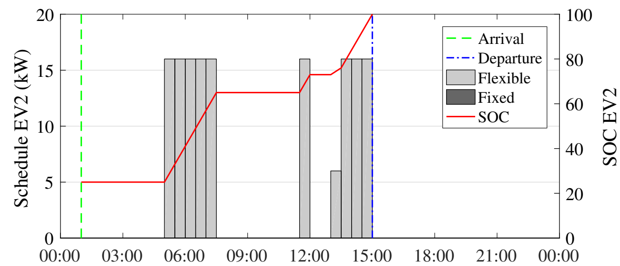


Fig. 9. Charging schedule for EV1

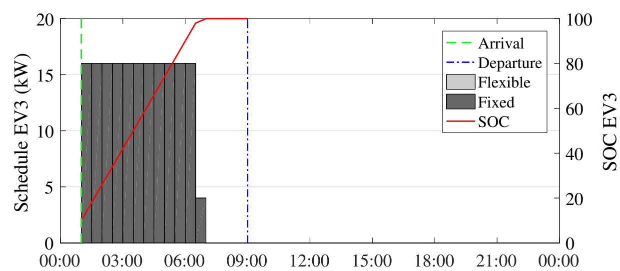


Fig. 10. Charging schedule for EV3

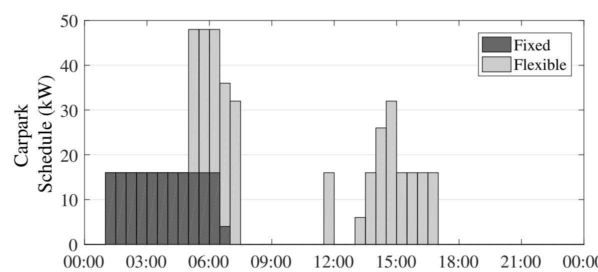


Fig. 11. Carpark charging schedule

charging schedule. The charging time requirement in relation to the desired SOC is represented in Equation (6). Equation (7) is considered to prevent overloading of the distribution transformer. The simulation results in [4] indicate that the economical charging feature can generate additional revenues for the carpark operators. Besides, the high-level controller is able to receive load interrupt request and participate in DR. They are the fundamental features of this carpark demonstrator.

## V. Experiment Results

To evaluate the performance of the demonstrator, the following experiments were carried out on the demonstrator platform.

### A. Charging scheduling algorithm test

Three vehicles are considered in the test scenario. The Uniform Singapore Energy Price (USEP) and the reserve price are used in the test case given in half-hour time interval. Fig. 7 presents the energy price and reserve price for the time period in the test case respectively. The time horizon is set to 24 h in the charging scheduling algorithm. This linear optimization problem is solved by using YALMIP [8] and CPLEX [9] solver. The charging scenario is considered as follows. Customer of EV1 is assumed to select fast charging mode and economic charging is preferred by EV2 and EV3. The charging schedule optimization results for the EVs are illustrated in Fig. 8 to 10 respectively, where both the scheduled charge power and SOC estimation are shown for each EV. The fixed charge power and the flexible charge power are both illustrated. During the charging process the load interruption request can be raised by the DSO. Consequently, the carpark operator interrupts the charging with flexible power and reschedules the it to a future time. Fig. 11 shows the fixed and flexible charge power schedule for the carpark.

### B. Demand response reaction time

As the round trip time of sending the request and receiving the signal between controller at two levels limits the information updating rate as well as the system reaction time, a round trip time analysis with Wi-Fi connection is carried out. Using the Labview program, the communication round trip time is measured for 1000 samples. The distribution is shown in Fig. 12. The maximal time is 367 ms and the mean value is 290 ms.

### C. Circuits parameters test

IEC 61851 has specified the CP circuit parameters to ensure the accurate signal transition between different EV status. The focus of the low-level controller test is on the correct EV status transition as well as a correct status detection on the EVSE. Hence the test is designed to measure the CP signal during the transition. Table I summarizes the CP circuit parameter test. Fig. 13 shows the example of measured rise time of CP signal from $-12$ V to 9 V. The result shows a rise time of 90 ns which

Table I
CIRCUITS PARAMETERS TEST

| Test type | Requirements | Results |
|---|---|---|
| Oscillator frequency | 1000 Hz ±5 kHz | 1000 Hz |
| CP signal voltage | voltage level ±1 V | within 1 V range |
| Pulse wave form test | Rise time: 5-10 µs, Fall time: 13 µs | Rise time: 90 ns, Fall time: 130 ns |
| Sequences diagnostics | see e.g. IEC 61851 | No violation found |

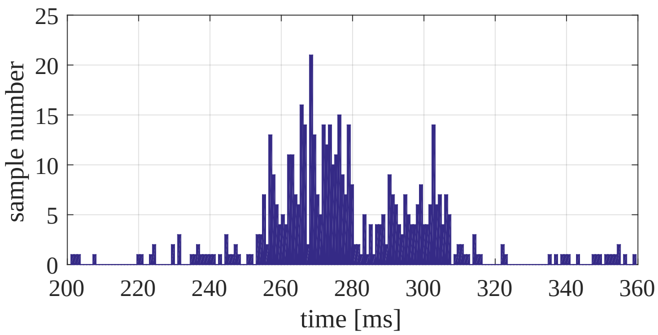


Fig. 12. Round trip time distribution of Wifi connection

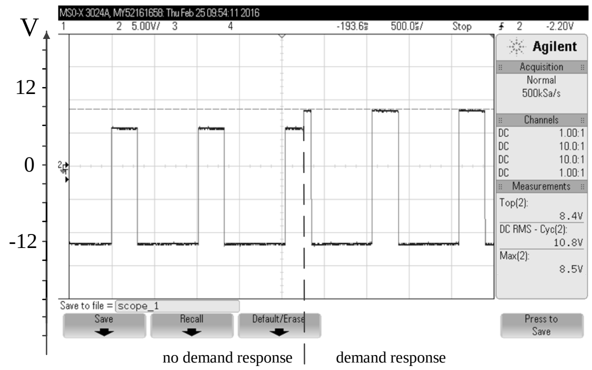


Fig. 14. CP signal transition of demand response

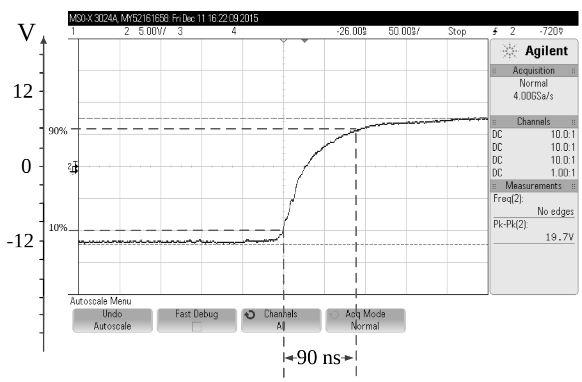


Fig. 13. CP circuits parameter test: rise time test

is less than the maximal of 2 µs. Fig. 14 shows the transition of CP signal status for the case that the carpark operator receives the load interrupt request.

## VI. CONCLUSIONS

The paper proposes a design of the demonstration system for carpark charging stations with demand response features. The two-level design compromises the low level controller in compliance with IEC 61851. The charging scheduling algorithm enables the carpark operators in the participation in the electricity market and his active role in providing support in the grid stability. Moreover, the digital communication between EV and EVSE, also specified as Vehicle-2-Grid (V2G) communication can bring further benefits to the provision of ancillary services and ease the the configuration process for the charing.

## VII. ACKNOWLEDGEMENT

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