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An Electric Vehicle Measurement System to Investigate the Pause and Resume Behavior of Electric Vehicle Charging

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***Abstract*—Electric vehicles (EVs) have significant potential to contribute to grid stabilization and operational optimization in behind-the-meter applications. A prerequisite for this is that EVs comply with external control requirements. In widely deployed AC charging systems, EVs are responsible for controling the charging power. To investigate this behavior, a measurement system is designed that captures the control signals of the charging station and records the power response of the EV at a high temporal resolution. This work presents the requirements and implementation of such a measurement system. The main requirements include time-synchronized measurement data acquisition and high temporal resolution, with power values sampled at 20 kHz and synchronized acquisition of the control setpoints. As an example application, the pause and resume behaviors of three EVs are analyzed. The results show that the resume process takes substantially longer than reducing the charging current to 0 A. While the longest pause process lasts approximately 5 s, the resume process can take up to 30 s. Among the investigated EVs, different patterns are observed, indicating that the pause and resume behavior is strongly vehicle-dependent.**

***Index Terms*—Electric Vehicle Charging, Energy Management System, Load Shifting, Smart Charging, Smart Grid**

Acronyms

CP	Control Pilot
EV	Electric Vehicle
EVMS	EV Measurement System
PE	Protective Earth
PP	Proximity Pilot / Proximity Pin
PWM	Pulse Width Modulation
SoC	State of Charge

I. Introduction

The electrification of the mobility sector is accelerating worldwide, with annual electric vehicle (Electric Vehicles (EVs)) sales already exceeding 17 million units and expected to surpass 20 million by 2025 [1]. This rapid expansion not only underscores the importance of EVs for decarbonizing transportation but also introduces notable challenges for distribution networks, where rising charging demand can lead to congestion and transformer overloading. Supporting reliable grid operation, therefore, requires a detailed understanding of charging behavior and the associated impacts on local infrastructure [2].

At the same time, the transition towards power systems dominated by variable renewable generation increases the need for distributed and rapidly responding flexibility resources. EVs, when intelligently controlled, offer substantial potential by shifting charging processes over time or temporarily pausing charging sessions to reduce peak demand. Conversely, the coordinated resumption of paused charging can provide negative balancing power, enabling EVs to absorb excess renewable generation and contribute to valley filling [3]. These application possibilities underline the potential of EVs to provide automatic Frequency Restoration Reserve (aFRR), particularly in low-inertia systems increasingly reliant on fast-acting demand-side resources [4], [5].

Flexibility from EV charging is also relevant in industrial environments. Charging stations colocated with production facilities or photovoltaic (PV) systems can help buffer rapid fluctuations in consumption or generation. These flexibility services depend critically on the dynamic response capabilities of both the EV and the charging infrastructure. In AC charging, the charging station communicates the allowed charging current to the vehicle via a Pulse Width Modulation (PWM) signal on the control pilot line of the charging cable, while the onboard charger inside the vehicle determines the actual power transfer. Recent studies indicate that ramp rates, transient behavior, and tracking performance vary considerably between EV models and charging technologies [6]. To investigate this behavior, high-resolution sensors are required to record the power transfer, as well as measurement equipment capable of reading the setpoints encoded in the PWM signal.

This paper presents a measurement system that enables time-synchronized recording of both power and the corresponding setpoints during AC charging. Based on this system, a comparative analysis of pause-and-resume charging behavior across three different EV models is conducted. By characterizing their responsiveness to externally specified setpoint changes, the study provides empirical evidence that is essential for assessing the suitability of EV fleets as providers of decentralized flexibility in modern power systems.

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II. Related Work and Contributions

Early investigations into grid services provided by EVs, such as primary frequency control, were conducted by Marinelli et al. [7], who validated a centralized approach using a test setup with series-produced electric vehicles. In their study, which included three Nissan Leaf, the charging current was adjusted based on a droop characteristic and communicated to the vehicles via the IEC 61851 standard. They showed that frequency control is technically feasible using EVs. However, as the analysis was limited to 1-second and 2-second windows, short-term transient behavior was not considered, and the corresponding measurement challenges were not discussed in detail.

Rauma et al. [8] highlighted the importance of detailed measurements by observing deviations between setpoints and the measured charge current. In experiments with a BMW i3 and a Nissan Leaf, currents were captured every second using a KoCoS EPPE PX power quality analyzer. Complementing this, Simolin et al. [9] investigated the influence of temporal resolution on the accuracy of charging station models in both residential and industrial settings. They concluded that a 1-second resolution is necessary for accurately modeling and controlling EV peak loads and energy consumption.

Recent research also addressed the conversion efficiency and grid interactions beyond active power. Sevdari et al. [10] validated the efficiency of onboard chargers (OBC) for 38 different EV models by comparing AC-side data from a DEIF multimeter with DC-side data from the Battery Management System (BMS) retrieved via the OBDII port. Most importantly, Sevdari et al. [6] concluded that commercial aggregators are targeting fast-reacting frequency products with overall delay requirements of only 1 to 2.5 seconds. To support this, they developed a custom demodulator capable of sniffing signals at a 20-ms resolution, offering a more cost-effective and compact alternative to commercial systems.

Comprehensive datasets are essential for advancing these models. Esser et al. [11] provided a high-temporal-resolution dataset for eight vehicle models, including bidirectional charging (V2G), with grid data captured using KoCoS EPPE PX analyzers and measurements requested at 500-ms to 1-s intervals with Unix timestamps. A major challenge identified in the literature is managing the limited predictability of vehicle behavior during start-stop operations. Brinkel et al. [12] highlighted that while pausing charging is economically beneficial during high-price periods, approximately one-third of tested car models enter a sleep mode from which they cannot easily resume. This issue stems from behaviors not explicitly defined in the IEC 61851 standard, whereas the newer ISO 15118 standard addresses it through specific wake-up triggers.

Collectively, these investigations show that reliable modeling and control require high-precision data that is often not publicly available. In particular, existing studies either rely on comparatively coarse temporal resolutions, focus on different measurement objectives, or provide only limited insight into how changes in the communicated setpoint are reflected in the electrical response of the vehicle. This paper addresses these gaps through the following contributions.

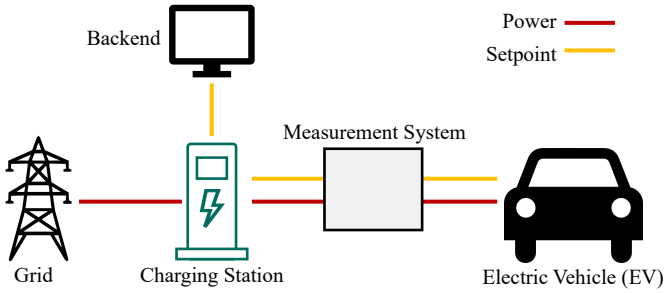


Fig. 1. The measurement system records power values and the setpoint signal between the charging station and the EV.

First, we derive a systematic set of requirements for time-synchronized measurement of both AC power and the PWM-encoded setpoint signal on the Control Pilot line, and present the hardware design of a purpose-built EV Measurement System (EVMS). The system achieves an adequate power sampling rate and Control Pilot (CP) signal resolution, enabling accurate decoding of setpoint steps without influencing the CP communication.

Second, using the EVMS, we present exemplary measurements of the pause and resume behavior of three representative EV models in response to externally imposed setpoint changes. In this work, the term “resume” denotes the procedure in which an active charging session is temporarily paused, resulting in no power transfer, and subsequently reinitiated to continue the charging process. In contrast, the term “pause” refers to the interruption of an active charging session, during which no charging power is transferred.

Third, by analyzing the captured transients, we show that unexpected phenomena during start and stop events occur on timescales of milliseconds to seconds, which are inaccessible to measurement systems operating at the 1-second resolution commonly reported in the literature [8], [9]. The presented measurements further reveal characteristic transient phenomena such as asymmetric phase ramp-up, stepwise current settling, and oscillatory plateaus, illustrating why high temporal resolution is essential for assessing the suitability of EVs as providers of ancillary grid services.

III. Measurement System

To derive the requirements for the measurement system, a detailed understanding of the sequence of an AC charging process is necessary. To avoid distortions in measuring the onboard charger’s reaction time caused by delays in transmitting the setpoint from the backend through the charging station, the setpoint is measured directly between the charging station and the EV. At this point, power, current, and voltage are also recorded (see Fig. 1). The following section first explains the fundamentals of AC charging and subsequently outlines the resulting requirements.

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A. Fundamentals AC Charging

In Europe, AC charging of electric vehicles is predominantly carried out using the Type 2 connector specified in IEC 62196-2 standard [13]. This connector supports single-phase and three-phase operation as shown in Fig. 2.

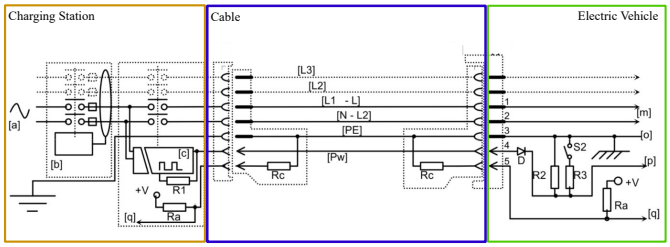


Fig. 2. Schematic of the Type 2 AC charging interface (IEC 61851, charging mode 3), showing the CP and PP circuits with the corresponding resistors for state signaling (R2, R3), cable identification (R_C), protective device (RCD), and the PWM control circuitry (q); adapted from [14].

The Type 2 interface comprises five high-current contacts for power transfer, the three line conductors L1 to L3, the neutral conductor N, and the protective earth PE. The two auxiliary pins CP and PP facilitate communication and safety functions. The PP provides cable identification via built-in resistance R_C and allows the charging station to verify the physical presence and current-carrying capacity of the connected cable. The CP serves as a bidirectional signaling interface through which the charging station communicates the allowable charging current to the vehicle using a PWM signal, while also enabling state detection throughout the charging process, which is shown in more detail in Fig. 3.

The CP interface uses a nominal 12 V DC source referenced to Protective Earth (PE) to signal vehicle presence and charging readiness. In the idle condition, when no vehicle is connected, the charging station maintains the CP line at approximately 12 V. Upon connection, the vehicle resistance R_2 pulls the CP potential to 9 V, indicating that a vehicle is detected but not yet ready to charge. When the EV closes switch S_2, the resistance R_2 is added in parallel, lowering the voltage to 6 V. The EV denotes that the vehicle is ready for charging and that energization is permitted once interlocks and safety checks are satisfied. Superimposed on the CP line is a PWM signal, at 1 kHz, whose duty cycle encodes the maximum allowable charging current by

$$I_{\text{maxCharging}} = D \cdot 0.6\ \text{A} \tag{1}$$

where D denotes the duty cycle of the PWM in percent. This formula is valid for the range:

$$10\% \leq D \leq 85\% \tag{2}$$

as defined by the IEC 61851 standard [13].

B. Requirements on Power Measurement

The transferred power during three-phase AC charging can reach up to 22 kW, corresponding to a current of 32 A. In order to analyze potential phase asymmetries, measurements must be performed on all individual phases. To avoid influencing the power transfer, the measurement equipment must be supplied externally so that it does not introduce additional load or distort the electrical signals. Moreover, to enable the future analysis of harmonic components, the sampling frequency of the measurement system must be at least 1.5 kHz.

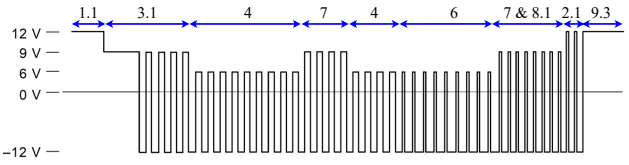


Fig. 3. Typical sequence of the Control Pilot (CP) signal during an IEC 61851 AC charging session: idle state with no vehicle connected (12 V, step 1.1), vehicle connected but not ready (9 V, step 3.1), vehicle ready to charge (6 V, step 4), temporary interruption initiated by the vehicle (9 V, step 7) followed by a return to the ready state (6 V, step 4), PWM duty-cycle changes indicating different allowable charging currents (step 6), termination of charging (9 V, steps 7 and 8.1), disconnection of the vehicle (12 V, step 2.1), and finally deactivation of the PWM signal (step 9.3).

C. Requirements on CP Setpoint Measurement

To evaluate the setpoint, the duration of the pulses of the 1 kHz PWM-Signal must be measured accurately. The maximum setpoint resolution provided by the OCPP backend is 0.1 A. With the PWM period of $T_{\text{PWM}} = 1\,\text{ms}$, the required temporal resolution Δt_{sample} can be determined to reliably distinguish current steps of $\Delta I_{\text{min}} = 0.1\,\text{A}$. To detect the shortest pulse possible, a factor of $\frac{1}{2}$ is added.

$$\Delta t_{\text{sample}} = \frac{1}{2} \cdot \frac{\Delta I_{\text{min}}}{0.6\,\text{A}} \cdot T_{\text{PWM}} \tag{3}$$

From this, a minimum temporal resolution of $\Delta t_{\text{sample}} = 833\,\text{ns}$ is obtained, corresponding to a sampling frequency of at least 1.2 MHz. Another requirement is that the measurement circuit must be according to the signal requirements specified in [15].

D. Requirements on Data Processing

The resulting requirements for data processing include the time-synchronous acquisition of the setpoints. Furthermore, it must be ensured that, despite the high sampling frequency, data can be continuously recorded and stored for the full duration of the charging process. Charging sessions of EVs can last several hours without pausing. Pause intervals must be added according to the total recording duration. In addition, the system should provide the capability to manually enter metadata, such as the vehicle model and the State of Charge (SoC) at the beginning and during the charging session.

E. Development of a Measurement System

The implemented measurement system, shown schematically in Fig. 4 with the components listed in Table I, consists of a power measurement module that records phase currents via current transformers. The current and voltage measurement points are sampled at 20 kHz and stored by a central

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TABLE I
MAIN HARDWARE COMPONENTS OF THE MEASUREMENT SYSTEM.

Component	Model
PLC	Beckhoff CX5330
PWM measurement terminal	Beckhoff EL1259
Power measurement terminal	Beckhoff EL3783
Current transformer	Janitza CT27

Programmable Logic Controller (PLC). The measurement modules are interconnected via EtherCAT [16], which ensures timestamp synchronization across all modules.

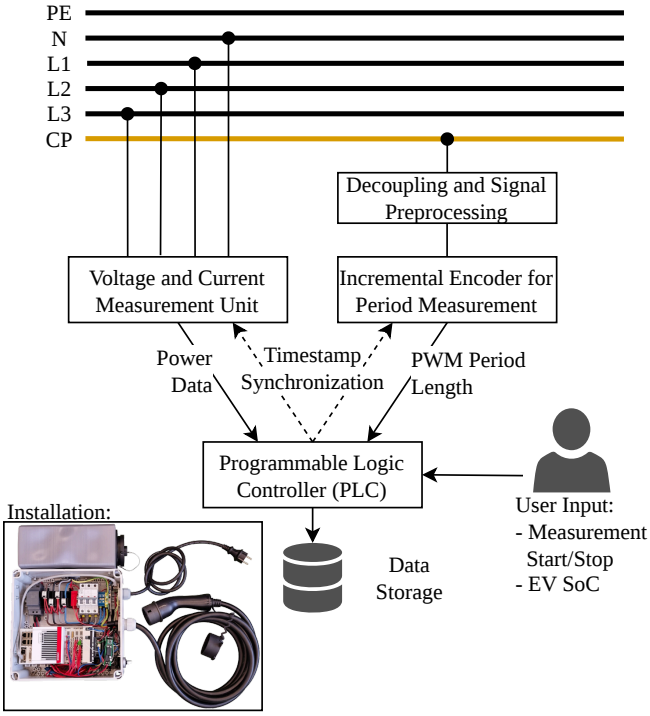


Fig. 4. Components of the measuring box and their hardware implementation

A user interface allows starting and stopping the measurements as well as entering the vehicle's SoC at specific points in time. To extract the power setpoint communicated by the vehicle via the CP line using a PWM signal, a dedicated "Decoupling and Signal Processing" board was developed, whose structure is illustrated in Fig. 5. A Schmitt trigger converts the PWM signal into a digital signal in the range of 0 to 5 V. An optocoupler provides galvanic isolation, ensuring that the CP signal cannot be influenced by the measurement system.

On the output side, the signal level is increased to 24 V to interface with the Incremental Encoder for Period Measurement, which determines the period length of the PWM signal.

IV. RESULTS

Based on the requirements derived in section III, we developed the measurement box presented in subsection III-E. It

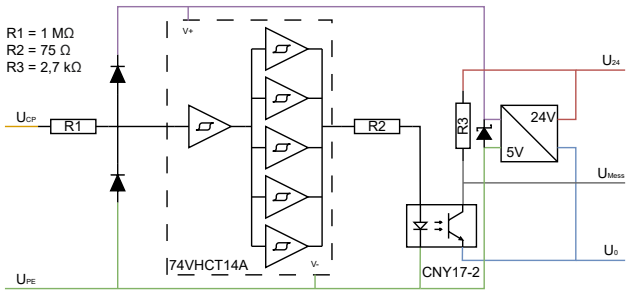


Fig. 5. PWM preprocessing and decoupling: The signal is transformed into a 5 V digital signal by the Schmitt-trigger and the optocoupler provides galvanic isolation.

enables high-temporal-resolution measurements to analyze the dependency between the control signal (PWM setpoint on the CP line) and the resulting electrical power transfer. Using the proposed measurement system, the pause and resume behavior of three vehicles (VW e-Golf, Tesla Model 3, and Hyundai Ioniq 5) is investigated exemplarily and discussed in detail in the following.

A. Resume Behavior

The resume behavior shown in Fig. 6 indicates that all vehicles initially enter a low-current energization phase. After 0.6 s to 1.8 s, the power electronics are energized with a small current in the range of 0.28 A to 0.5 A. This state is maintained until, after approximately 3.5 s to 22 s, the current is increased towards the steady-state level (here corresponding to a setpoint change from 0 A to 16 A). For the VW e-Golf and the Tesla Model 3, the phase currents are not increased synchronously across all 3 phases but rather sequentially. In addition, the VW e-Golf and the Hyundai Ioniq 5 exhibit short current spikes. The Hyundai Ioniq 5 further shows distinct current dips while increasing the current in the range between 8 A to 10 A.

B. Pause Behavior

The pause behavior in Fig. 7 also differs between the investigated vehicles. After a setpoint change from 16 A to 0 A, the vehicles start reducing the charging current after 0.09 s (VW e-Golf), 0.04 s (Tesla Model 3), and 0.08 s (Hyundai Ioniq 5). For the VW e-Golf, the current is reduced stepwise via multiple plateaus that are regulated with overshoot and settling behavior, reaching 0 A after 5.1 s. In contrast, the Tesla Model 3 and the Hyundai Ioniq 5 reduce the current in a ramp-like manner to an intermediate plateau of 0.3 A (Tesla Model 3) and 0.7 A (Hyundai Ioniq 5). This plateau is reached after 0.1 s (Tesla Model 3) and 0.88 s (Hyundai Ioniq 5). Subsequently, the current is held until approximately 0.56 s (Tesla Model 3) and 2.2 s (Hyundai Ioniq 5), before dropping to 0 A. Notably, the shutdown ramp of the Hyundai Ioniq 5 is not perfectly linear.

C. Summary

Comparing the three vehicles reveals both commonalities and clear vehicle-specific differences. In all cases, resuming

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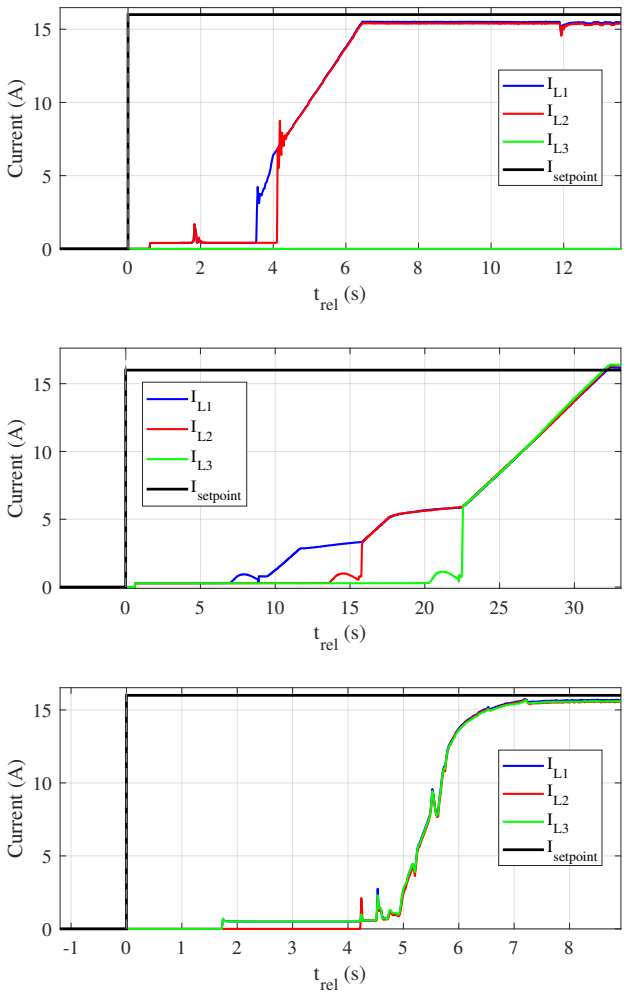


Fig. 6. Currents (I_{L1}, I_{L2}, I_{L3}) of the EVs when Resuming the Charging Process (Set-Point Change from 0 A to 16 A) of the VW e-Golf (top), the Tesla Model 3 (middle) and the Hyundai Ioniq 5 (buttom)

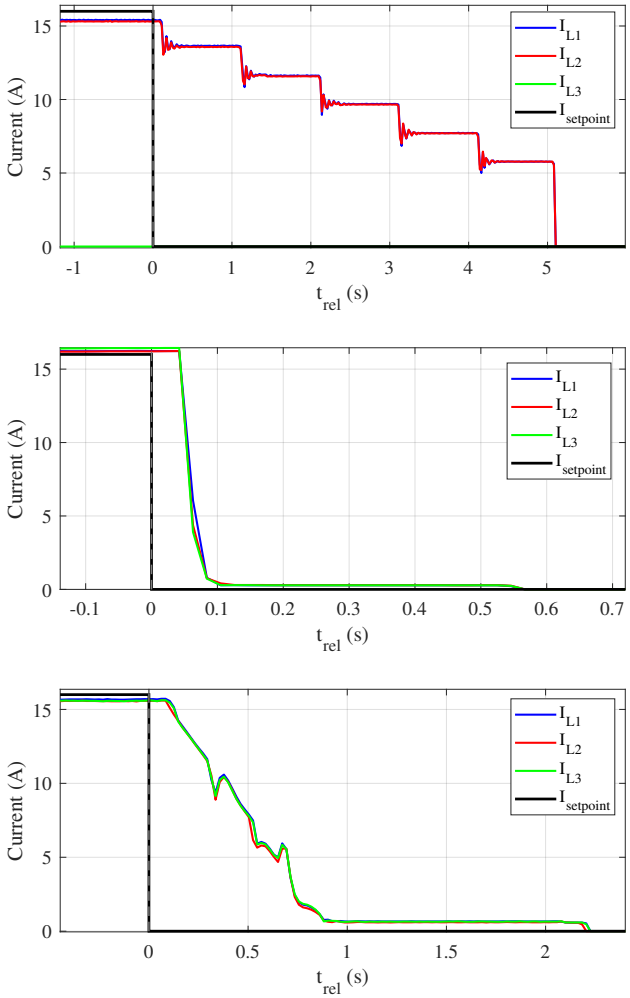


Fig. 7. Currents (I_{L1}, I_{L2}, I_{L3} of the EVs when Pausing the Charging Process (Set-Point Change from 16 A to 0 A) of the VW e-Gold, the Tesla Model 3 and the Hyundai Ioniq 5

charging includes an initial low-current phase in which the power electronics are energized before the current rises to the steady-state level. Similarly, when pausing charging, an intermediate low-current phase is typically observed before the current reaches 0 A. Overall, the resume process takes substantially longer than reducing the charging current to 0 A.

V. Discussion

The results in section IV show that key transients of the pause and resume process occur on time scales ranging from subseconds to several seconds. Capturing these dynamics requires temporally high-resolution, time-synchronized recordings of both the PWM-encoded setpoint on the CP line and the electrical quantities at the AC interface. The proposed EVMS addresses this need by sampling voltage and current at 20 kHz while simultaneously enabling high-resolution setpoint acquisition, thereby allowing the relevant fast transients to be resolved without delays of processing times of backend and charging station.

Beyond the time-scale aspect, the exemplary measurements highlight that pause and resume behavior is strongly vehicle-specific. Differences are observed both across phases and across vehicles, for example in the sequential phase current increase during resuming, as well as in distinct settling and oscillatory effects during current regulation. Similarly, the shutdown response differs substantially between the considered vehicles, with some reacting within less than 0.1 s while others require several seconds (up to 5 s) to reach 0 A. These observations underscore that accurate modeling of pause and resume behavior cannot be captured by a single generic template but should reflect the vehicle-dependent characteristics of the onboard charger and its control strategy.

Finally, these findings are relevant when considering EV charging as a controllable flexibility resource for fast grid services. Recent work on EV aggregation emphasizes that commercial applications increasingly target fast-reacting frequency products with stringent overall delay requirements on the order of 1 s to 2.5 s. In this context, the measured

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heterogeneity raises practical control questions for aggregated fleets: whether it is preferable to modulate current setpoints of already-charging vehicles, or to rely on stop-and-resume actions, and which response speeds are sufficient for the intended service. Moreover, short-term oscillations and non-monotonic settling during ramps may affect both tracking performance and the predictability of the aggregated response, suggesting that stability-aware control and vehicle-specific parameterization can be important for reliable service provision.

VI. Conclusion

Electric Vehicles (EVs) have significant potential to support grid operation through fast demand-side flexibility and to improve behind-the-meter operation. Realizing this potential requires EVs to reliably follow external charging setpoints. In widely deployed AC charging systems, the onboard charger (OBC) implements these setpoints locally and, therefore, assessing controllability requires a measurement approach that captures both the charging station control signal and the EV-side electrical response at high temporal resolution.

This paper presents the requirements and the implementation of a dedicated measurement system for the analysis of AC charging. A key design aspect is the time-synchronous acquisition of setpoint and power quantities. The PWM-encoded setpoint on the Control Pilot line is captured with a sampling frequency of $1.2\,\mathrm{MHz}$ using a dedicated signal-conditioning circuit designed to minimize interference with the original signal, while voltage and current are recorded at up to $20\,\mathrm{kHz}$.

As an exemplary application, we analyze the pause and resume behavior of three EV models. The measurements indicate that resuming charging can take substantially longer than reducing the charging current to zero. While the longest pause event in the presented examples lasts approximately $5\,\mathrm{s}$, the resume process can take up to $30\,\mathrm{s}$. Pronounced differences between vehicles are observed, highlighting that pause and resume dynamics are strongly vehicle-specific and should be explicitly considered in modeling and control design.

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Author Contributions

Author contributions according to Contributor Roles Taxonomy (CRediT, https://credit.niso.org/): *Conceptualization:* S.B., A.S.; *Data curation:* S.B.; *Formal analysis:* S.B.; *Funding acquisition:* V.H.; *Investigation:* S.B., A.S.; *Methodology:* S.B., A.S.; *Project administration:* S.B., F.W., S.W., V.H.; *Resources:* V.H.; *Software:* S.B., M.D.; *Supervision:* F.W., S.W., R.J., M.H., V.H.; *Validation:* S.B.; *Visualization:* S.B., A.S.; *Writing - original draft:* S.B., A.S.; *Writing - review and editing:* S.B., A.S., F.W., R.J., S.W., M.H., V.H.

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