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Metrological Characterization of a Vehicle's Charging Profile for Smart Charging Applications

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Sommario – **In the latest years, the concept of smart charging has emerged as a necessity for the optimal management of power grids with high penetration of electric vehicles and renewable power generation. Based on this, the aim of the present work is filling a gap in the literature about the metrological characterization of electric vehicles connected at the charging station. In particular, a Charging Point Management System based on the Open Charge Point Protocol is developed and then integrated into an ICT system to support the charging of electric vehicles via wallboxes installed at the University of Brescia (Italy). Subsequently, smart charging functionalities are implemented to control current-based charging and these are investigated statically, as for example by characterizing the power factor as a function of the requested current, and dynamically, by inquiring the response time of the communication and the current resolution limits.**

I. INTRODUCTION

Integrating renewable energy sources into the charging pipeline of Electric Vehicles (EVs) [1] is essential to meeting Greenhouse Gas (GHG) emission reduction [2] targets and effectively combating climate change. In fact, the energy sector is the primary contributor to GHG emissions, with the transportation sector being a significant energy consumer. For instance, in 2022, transport activities accounted for 31.0% of the European Union's final energy consumption. The growing share of renewable energy production and the transition to Electric Vehicles (EVs) introduce new challenges for the operation and management of power grids [3, 4], particularly due to uncertainties in both energy generation and consumption. The uncoordinated charging of vast amounts of EVs might negatively affect peak load and transformer loading and might advocate for grid upgradation costs. The smart charging [5, 6] has hence evolved as a game changer, in that the adaptivity of the charging process not only might limit the above drawbacks, but might also contribute to the smooth functioning of the power grid, as for example by stabilizing the power grid [7], by optimizing the exploitation of renewable power sources [8],by minimizing costs and optimizing tariffs [9].

A. *Related Works*

In such a context, measurements are fundamental in order to characterize the responsiveness of the communication between the EV and the Charging Station (CS) and to evaluate the real energy efficiency during the recharging process. Despite this, to the best of the authors' knowledge, there is a very limited number of works related to metrological aspects of the charging process. The work in [10] deals with the realization and testing of field equipment for metrological verification of the metering subsystem inside electric vehicle supply equipment and an accurate estimation of the energy absorbed by a battery electric vehicle is provided. In the following work [11], the underlying principle of smart charging (forcing the EV to draw different current levels) is contemplated, but the core of the study is on the communication between the EV and CS and a Man In the Middle approach is proposed and tested. These works are part of an European project, outlined in [12], in the context of which a devoted laboratory has been developed (described in [13]).

B. *Objectives*

Based on the identified research gap, the objective of this work is developing a CPMS (Charging Point Management System), a software for managing charging processes based on the OCPP (Open Charge Point Protocol) which is then integrated into an ICT system to support the charging of electric vehicles via wallboxes installed at the University of Brescia (Italy). Subsequently, smart charging functionalities are implemented to control current-based charging, and algorithms are developed to achieve a metrological characterization of a vehicle connected to the charging network. This characterization aims to understand the vehicle's features and determine how it can be utilized in a smart grid context to help balance the grid when needed.

II. MATERIALS AND METHODS

A. *The ICT Infrastructure*

The diagram in Figure 1 illustrates the ICT infrastructure used for charging, which consists of:

- **The CPMS**, the software developed for managing the charging process;

- **The CS** connected to the grid to enable the charging of electric vehicles;
- **Smart Meter, UPM209 Network Analyzer**: The charging station provides information on the energy supplied via OCPP, but these are not sufficient for a metrological characterization. Therefore, an additional meter was added at this aim. In our case, we monitored values such as current, phase shift, active, reactive, and apparent power, as well as absorbed and supplied energy, to perform a characterization of the vehicle. The UPM209 network analyzer supports a measurable voltage range from 10 V to 285 V RMS (phase-to-neutral) and from 17 V to 495 V RMS (phase-to-phase), depending on the wiring configuration, and enables FFT-based harmonic analysis only above 20 V RMS for voltage and 200 mA for current. To ensure data reliability, measurements are automatically disabled outside these ranges, with overflow conditions clearly indicated in compliance with EN 61010-2-030. From a metrological perspective, the device guarantees typical accuracies within specified operating ranges: ±0.2% of the reading for voltage measurements between 10% and 100% of full scale, ±0.4% for current measurements between 5% and 100% of full scale, ±0.5% for active power (at power factor = 1), and ±0.1% for frequency. It complies with Class 1 accuracy for active energy according to IEC/EN 62053-21 and Class 2 for reactive energy as per IEC/EN 62053-23. The accuracy of the device guarantees that the experiments indicated in Section D. are distinguishable the one with respect to the other.

In Figure 2, the structure of the CPMS is reported. Specifically, the developed CPMS consists of:

- **A main block**, which is the main Charging Management System (CMS).
- **A relational database**, with which the CMS interacts using the Python library `psycopg2`.
- **A time-series database**, used to store data from smart meters via the `InfluxDB` library.
- **The pymodbus library**, which allows the implementation of the `Modbus protocol` in Python to enable communication with smart meters.
- **The OCPP 1.6 library by Mobility House**, based on JSON, to enable communication between the CPMS and the EVSE.
- **Functions for generating charging profiles**, capable of calculating the current value to be supplied to the vehicle.

B. *The Open Charge Point Protocol*

The OCPP protocol, based on WebSocket, represents the standard for communication between the CPMS and the CS, defining all possible messages that the two parties can exchange and the payload of each. In particular, since the version of OCPP implemented by Mobility House was used, the exchanged messages are simply JSON. Each communication is based on two messages:

- A **req** message, through which a request is sent.
- A **conf** message, through which the response is sent.

This protocol also includes smart charging features, allowing the CPMS to set charging profiles that impose current limits.

C. *Measurement Protocol And Smart Charging Characterization*

The procedure is the following:

- The vehicle is connected to one of the available charging stations via a Mennekes cable. In this way, the signal sent from the station to the car through the Control Pilot (a wire in the connector) changes from a voltage of 12V to 9V (according to the IEC 61851), indicating that a vehicle is connected.
- Next, the RFID tag is scanned: the charging station can then read the identification and send an Authorize request via OCPP to the CPMS, which will verify the presence of the identification in the database and send a response to the authorization request.
- If the authorization is granted, the signal voltage will drop to 6V, indicating that charging can begin.
- The desired current limit is calculated and sent to the charging station via the appropriate OCPP functionality.
- Once the station receives the limit, it will impose it on the vehicle: specifically, the current value for charging is described by the duty cycle value of the signal exchanged through the Control Pilot, following the IEC 61851 protocol.
- Once the desired limit has been set, the charging parameters are read using UPM209 devices. The measurements typically included currents, active power, reactive power, apparent power, and the power factor.
- Once these values are acquired, they are stored both in the time-series database to keep track of the parameters associated with the transaction and in a .csv file to facilitate future analyses.

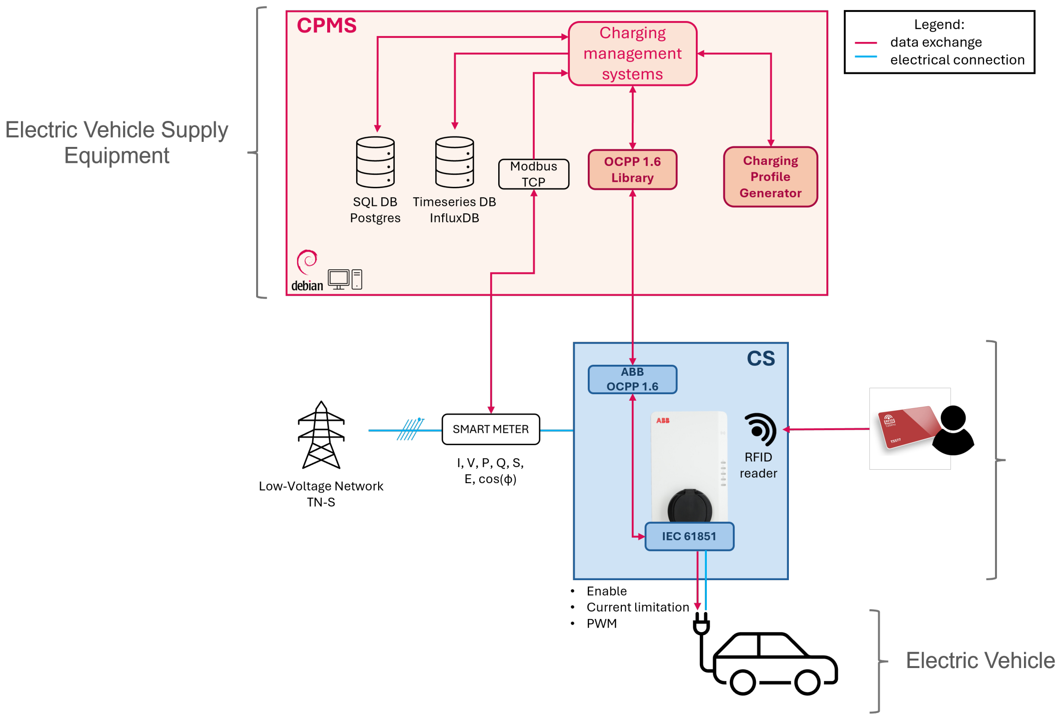

Fig. 1. Conceptual layout of the ICT infrastructure.

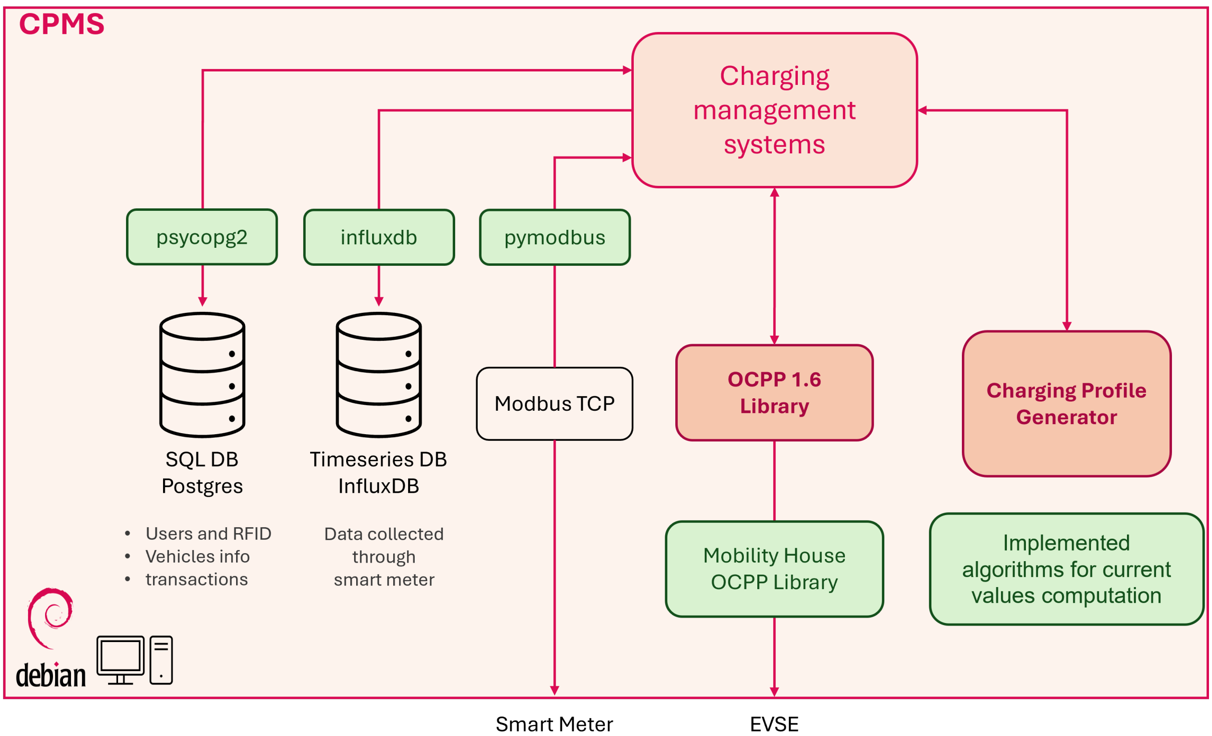

Fig. 2. The structure of the CPMS.

D. The Experiments

Several tests are conducted aimed at obtaining a metrological characterization of the charging profile of a specific vehicle. An electric Renault Zoe has been employed, and two ABB wallboxes, one single-phase and one three-phase, located in the university parking lots. In particular, two types of experiments have been carried out:

- **Stationary charging profile**: Sweep tests with linear steps of 1 A of imposed current are performed, in order to characterize the upper and lower limits of current absorption and the power factor associated with each current value. The objective is the creation of power-based charging profiles. The current set point is updated each 30 seconds.
- **Dynamical charging profile**: An essential characterization of the charging station has conducted to determine the resolution and accuracy of the current response, the response time to the commands sent, and the behavior in response to sudden changes in the imposed current limits, i.e., the step response.

III. RESULTS

A. Stationary Charging Profile

The results for the sweep test in the single-phase case are reported in Figures 3 and 4. From Figure 3, it arises that there is a lower current threshold, which is 6 A. The upper limit, however, contrary to what is stated in the wallbox specifications, turns out to be 16A instead of 32A, indicating that some settings of the station may have been modified. A power factor higher than 0.9 can be achieved only by requesting more than order of 8 A.

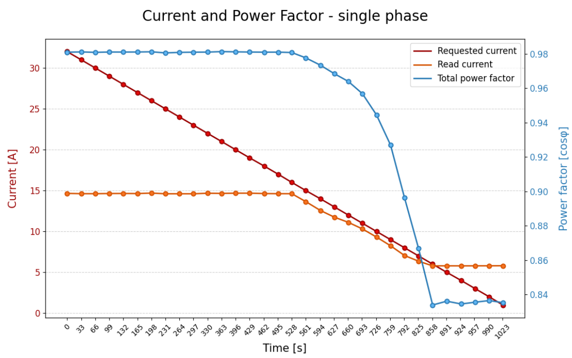

Fig. 3. Requested and actual current and power factor for the descending sweep test in the single-phase case.

The results for the three-phase sweep tests are reported in Figures 5 and 6. For requested currents lower than 7 A, the vehicle behaves as a generator rather than as a load, as it has been confirmed by further discharge tests which will be reported in the full paper version. For requested currents higher than approximately 9 A, the power factor has

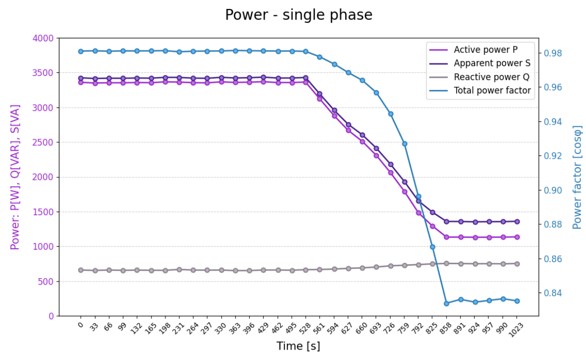

Fig. 4. Active, reactive, apparent power and power factor for the descending sweep test in the single-phase case.

quite high values, with a minimum of 0.86 for 12 A. From Figure 5, a mismatch between requested and measured current is highlighted especially as long as the current increases. This result motivates the further analyses conducted in Section B..

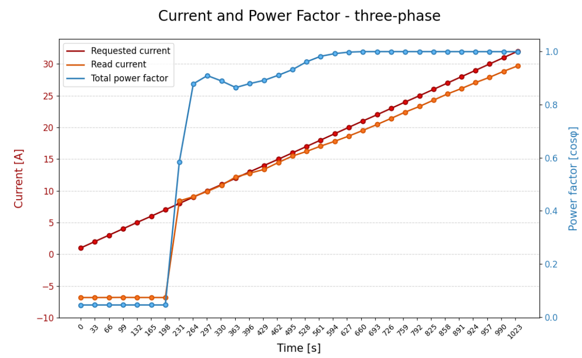

Fig. 5. Requested and actual current and power factor for the ascending sweep test in the three-phase case.

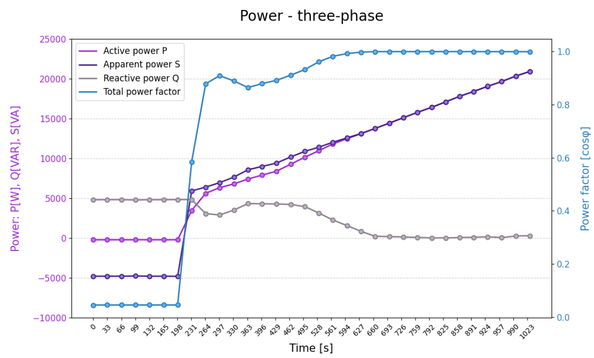

Fig. 6. Active, reactive, apparent power and power factor for the ascending sweep test in the three-phase case.

B. *Dynamical Charging Profile*

The results reported in Figure 7 refer to a test during which the requested three-phase current has been varied from 0 to 32 A every 10 seconds, with steps of 0.1 A. By varying the current with a finer grain compared to what was done in the sweeps, a step-like behavior in the current was observed, as different set current values corresponded to the same measured reading. In this test, for set limit values between 8 and 13 A, the measured current sometimes appears to exceed the limit of requested current. However, when plotting the current value multiplied by the power factor, it becomes evident that the current actually contributing to the active power never actually exceeds the set limit. This implies that if algorithms are to be developed to control charging based on power, the active power P used for charging would never exceed the limit value calculated using the formula $V \cdot I$.

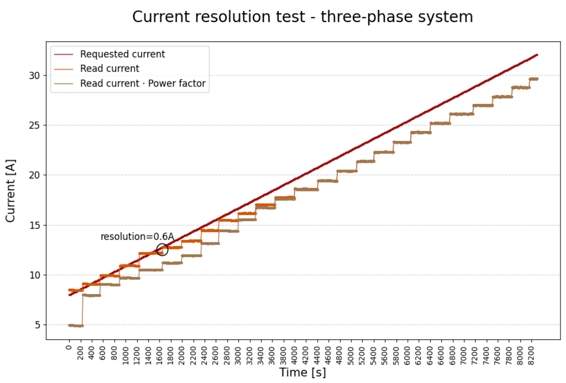

Fig. 7. Current resolution test.

IV. DISCUSSION

Future developments of the present work include the integration of a Blockchain into the implemented ICT system. This would facilitate local transaction management while enabling the adoption of smart contracts, which could dynamically adjust charging power based on demand, ultimately helping to reduce costs. Another possible extension of this work could be the development of Vehicle-to-Grid (V2G) regulation algorithms [14, 15, 16, 17], allowing the vehicle to function as a generator, supplying power to the grid to help balance it when needed. For these applications and in general for managing a fleet of vehicles, it is fundamental to have a reliable metrological characterization of the power flows, as done in this work.

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