

Charger tester solution with embedded SelfTest architecture for electric vehicle charging station diagnostics

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Abstract

The article presents an engineering concept for diagnostic testing and fault detection in electric vehicle charging systems, supported by a review of relevant design and testing methodologies. Particular emphasis is placed on a simulation-driven concept that incorporates an integrated self-diagnostic system with an internal test module. This proposed architecture enables automated evaluation of the operational status of power electronic components within the charger's structure. Its primary goal is to enhance system reliability and ensure safe operation for users, while minimizing the need for external maintenance. The paper also addresses key challenges and practical considerations in implementing such a system, outlining potential benefits, such as simplified technical support, and limitations, including integration costs and scalability. Additionally, the article compares charging parameters for the developed testers with those from a simplified lithium-ion battery simulation model.

Keywords: maintenance, fault detection, electric vehicle supply equipment, artificial power electronics load, autonomous diagnostics

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Highlights

- The tester verifies correct operation of electric vehicle charging stations.
- Simulates real charging conditions using artificial power electronics load.
- Overview of available methods for testing charging stations.
- Analysis of advantages and limitations of diagnostic tools.
- Preliminary laboratory research of charger tester.

1. Introduction

With the growing adoption of electric vehicles, ensuring the reliability of their charging [1,2] process has become a critical factor for both safety and user comfort [3–5]. Malfunctions in the charging unit may lead to incomplete charging of the electrochemical battery, a reduction in its service life [6–9], vehicle failure [10–12], or even adverse effects on the power grid infrastructure [13,14], which may affect the parameters of the power grid [15], the determination of which is crucial for the operation of power electronic devices characterized by high quality of electricity [16–18]. If the permissible power quality

standards are exceeded, it may be necessary to use specialized compensation devices, such as active parallel compensation [19–23], or face legal consequences, including financial penalties for violating applicable regulations.

The continuous development of battery technology in recent years has significantly improved the performance of electric vehicles, primarily through increasing driving range and reducing charging times [24]. This trend is particularly relevant for applications such as electric buses, whose operational capability strongly depends on the availability of appropriate charging infrastructure. The limited capacity of on-board batteries significantly affects their achievable range, especially on longer routes [25,26].

In cases of charger malfunction, a battery management system (BMS) may mitigate damage to the electrochemical storage unit [27–29]. Nevertheless, even with active BMS intervention, the battery may be exposed to transient current surges or insufficient energy delivery. Such conditions can result in partial charging, consequently limiting driving range

and impairing overall vehicle functionality.

Recent studies using the CRITIC method further indicate that criteria related to battery charging and vehicle energy consumption play a decisive role in the selection of electric vehicles, highlighting the importance of reliable and efficient charging systems [30].

The broader context of modern transportation systems, including alternative propulsion technologies and maintenance strategies, also provides relevant background for the development of intelligent diagnostic methods in electric mobility [31,32].

The rapid expansion of electric vehicle (EV) charging infrastructure has shifted research attention from purely technical aspects of chargers toward broader issues of planning, management, and long-term reliability. Recent studies propose advanced decision-making frameworks for improving charging-network performance, including fuzzy-logic models for infrastructure enhancement [33], investment-strategy optimization for charging-station deployment [34], and multi-criteria methods for selecting optimal station locations [35]. Other works emphasize the role of data-driven analysis in operational management of charging networks [36].

Within this context, the SelfTest concept introduced in this paper addresses an essential but underexplored dimension of EV-charging-infrastructure reliability: autonomous, embedded diagnostics. While existing literature focuses on where and how charging stations should be deployed, far less attention is given to ensuring their continuous operational availability once installed. The proposed SelfTest architecture complements planning and decision-making approaches by enabling preventive diagnostics, reducing maintenance-related downtime, and improving long-term station reliability. As such, SelfTest integrates naturally into modern infrastructure-management frameworks and supports the sustainable development of EV charging networks.

Therefore, rigorous charger testing is essential to ensure high efficiency, operational stability, effective energy transfer, and compliance with applicable standards. These tests may include evaluation of electrical parameters, environmental assessments, electromagnetic compatibility (EMC) verification, and simulations of various charging scenarios.

The large scale deployment of EV charging infrastructure

presents new challenges for engineers, involved in a power system testing, particularly concerning the maintenance of installed AC and DC charging units in public environments. Numerous electric vehicle supply equipment (EVSE), commonly referred to as charging stations, require regular testing and preventive maintenance at defined intervals [37]. The importance of testing EV charging infrastructure increases as a growing share of the power system is supplied by inverter-based renewable energy sources [38–40]. Consequently, research efforts worldwide are focused on developing advanced diagnostic and verification solutions, tailored for EV charger systems [41–44]. However, these studies focus on external Plug&Test testers. Plug&Test testers are external diagnostic devices designed for evaluating EV chargers. Their operation relies on the fact that a service technician connects the tester directly to the charger's output cable [45], thereby emulating the presence of an EV and enforcing predefined current–voltage profiles. The tester acts as an independent measurement unit, not integrated into the charger, and can be used in any service environment.

In practice, they represent standard service equipment, although their use requires physical access to the charger and manual configuration of the diagnostic procedure.

A key novel contribution introduced in the present study is the development of a tester integrated directly into the charger's structure, which will be referred to throughout the manuscript as the SelfTest tester. This solution significantly extends conventional diagnostic approaches by enabling internal testing without the need for external measurement equipment, thus allowing for autonomous monitoring of the charger's condition and its power-conversion components.

The introduction of the SelfTest tester provides new opportunities for on-board diagnostics and monitoring of converter operating parameters, representing an important contribution to the advancement of reliability assessment methods for traction battery chargers.

Electric charger testers can be applied across a wide range of sectors, including design offices that specialize in developing advanced charging systems. Li-ion batteries, which are commonly used in modern portable and industrial applications, are considerably more sensitive than cells based on other chemistries and exhibit a low tolerance for improper operating

conditions. Consequently, chargers intended for Li-ion batteries must maintain highly accurate control of both current and voltage. Even minor deviations from the required parameters can result in incomplete charging, reduced battery lifespan, or noticeable degradation of performance.

Given these strict requirements, it is essential to thoroughly evaluate chargers across their entire operating range. However, performing such tests with actual batteries as the load is often impractical and time consuming in both laboratory and production environments. To address these challenges, battery emulation systems have been developed, enabling fast, repeatable, and realistic testing of chargers without the need for physical battery cells. Their use significantly shortens the time required to evaluate charger prototypes, as they eliminate the need to configure and handle various types of electrochemical batteries during testing.

This paper focuses on the evaluation of off-board electric vehicle chargers. Its primary objective is to develop a diagnostic tester, that enables autonomous self-assessment and supports fault detection. The application of such a solution significantly reduces testing and maintenance costs, by automatically verifying device functionality. The diagnostic objective is to assess the functional and electrical performance of the EV charger, in particular:

- verifying the correctness of the generated voltages and currents, including their limits,
- analyzing the system's behaviour under dynamic and overload conditions,
- evaluating the complete charging profile within a matter of minutes,
- detecting faults that may affect user safety, charging efficiency, and the proper operation of the battery.

This enhances the efficiency of the diagnostic process, contributing to greater availability and reliability of charging systems or lowering maintenance expenditures.

Industrial charger diagnostics lack a method for safely, repeatably, and cost effectively testing device behaviour under various load profiles. Physical loads are expensive, difficult to scale, and do not allow for the rapid generation of dynamic test scenarios. The scientific challenge is to develop a method that allows for programmatic load modelling while maintaining diagnostic reliability.

This study hypothesizes that implementing a programmable load-emulation method within an autonomous diagnostic tester enables reliable, repeatable, and cost-effective evaluation of EV charger performance under dynamic conditions. An additional research challenge present in this system is the interaction between the two converters — the charger and the tester — when both sides of the DC bus are equipped only with limited DC bus capacitance, and the DC bus is supplied by a single-phase power factor correction (PFC) stage. Such a PFC introduces 100 Hz voltage oscillations on the DC bus, which may affect energy circulation, control system and influence the overall stability of the converters.

In a real system with a battery, the DC bus is inherently stabilized by the battery, which acts as a large low-impedance energy buffer. In the present case, this stabilizing effect is absent, meaning that all transient states directly affect the operation of both converters. This phenomenon becomes particularly significant when large amounts of energy circulate between the charger and the tester.

2. A Plug&Test tester of charger

In this approach, diagnostic devices are proposed, that do not interfere with the internal circuits of the charging station. Their connection procedure mirrors that of an electric vehicle, allowing for seamless integration. The devices remain connected for several minutes to analyse key parameters of the charging process. Thanks to their mobile design, such as integration into a vehicle, these systems enable infrastructure diagnostics across various locations, while maintaining high portability.

From the standpoint of proper charger operation, the most critical parameters include:

- charging voltage,
- charging current,
- current ripple,
- the overall charge profile.

The diagnostic device should emulate the behaviour of an electrochemical battery, enabling rapid acquisition of the full charge curve, from 0% to 100%, within approximately one minute. However, charging stations typically supervise the charging procedure by estimating the time required for each stage. This built in functionality would prevent rapid execution

of a complete charging cycle test. Therefore, the charger must be equipped with an additional service mode function to disable time based restrictions during diagnostic operation. Furthermore, such a tester must incorporate a Controller Area Network (CAN) [46–49], allowing simulation of communication with the BMS of the electrochemical storage unit [50].

Upon completion of the charging curve measurement, the obtained data is compared against a reference profile defined by the manufacturer, for the specific type of electrochemical battery. If significant deviations from the benchmark values are detected, the charging station may be designated for further diagnostics, which could require direct intervention in its internal systems.

The diagnostic device can operate in three configurations, with respect to the management of electrical energy at the charger tester's output. The processed electrical energy may be:

- used to charge an electric vehicle or an electrochemical battery pack (Figure 1a),
- returned to the power grid (Figure 1b),
- dissipated in the form of heat (Figure 1c).

From an economic perspective, specifically with regard to return on investment (ROI), the final energy management option, dissipation as heat, is the least efficient but also the simplest and most cost effective to implement. Assuming the charger test duration does not exceed one minute, energy losses due to dissipation are negligible, in the context of overall diagnostic costs. However, if it is necessary to diagnose the charging curve at a time, corresponding to the actual charging process, a solution enabling energy return to the network takes on significant economic and practical importance, because in the case of studying the charging curve on a real object, such as an electric vehicle battery, the analysis is limited to its current charge level. Consequently, it is impossible to carry out a full study of the entire characteristic of the charging process or to quickly repeat it, due to the need to discharge the electrochemical battery.

The charger tester enables precise shaping of the voltage characteristics, allowing for the execution of arbitrary charging curve profiles, tailored to various types of electrochemical batteries [51]. Furthermore, the device is capable of generating a stable and an accurately defined voltage value, facilitating the

simulation of any operating point, within the electric vehicle charging station's profile. This capability allows for controlled testing of charger responses under extreme conditions, such as deep battery discharge or overcharging, which are crucial for assessing the safety and efficiency of the overall charging process.

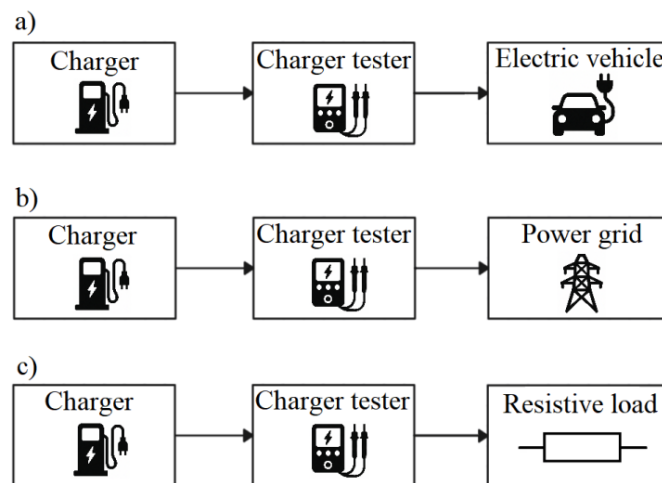


Figure 1. Block diagram of the electric vehicle charger testing system: (a) configuration with battery charging, (b) configuration with energy recovery to the power grid, (c) configuration with energy dissipation through resistive load.

3. Concept of the novelty SelfTest tester of charger

For simulation studies, an automatic charger tester configuration was selected, that is embedded within the charging unit, without lacks galvanic isolation. The simulation model accounts for parasitic resistances of capacitors and inductors, as well as voltage drops across semiconductor components. The chosen setup, illustrated in Figure 2, does not allow for comprehensive testing of all power converters integrated into the charger, as the AC/DC block with PFC, processes only the internally dissipated energy in the form of thermal losses, during the test. A classical PFC solution was used in the input section of the system. The PFC consists of a diode bridge and a DC/DC boost converter [52]. For the implementation of the output stage, that is responsible for supervising the battery charging process, a DC/DC buck converter was chosen.

The mathematical description and circuit diagrams of the DC/DC boost and buck converters used in this study, including parasitic resistances, are presented in [53]. The numerical values of the individual resistances are provided in Section 4.2

as part of the power-loss calculation.

The AC/DC PFC block can undergo self-diagnostic procedures by monitoring the quality parameters of the DC bus voltage, including ripple, average value fluctuations, and voltage rise rate, upon activation. Simultaneously, the magnitude and waveform of the input current, during standard electric vehicle charging, can be analysed. Additionally, a comprehensive evaluation of the PFC block's performance may involve injecting controlled disturbances, such as brief load

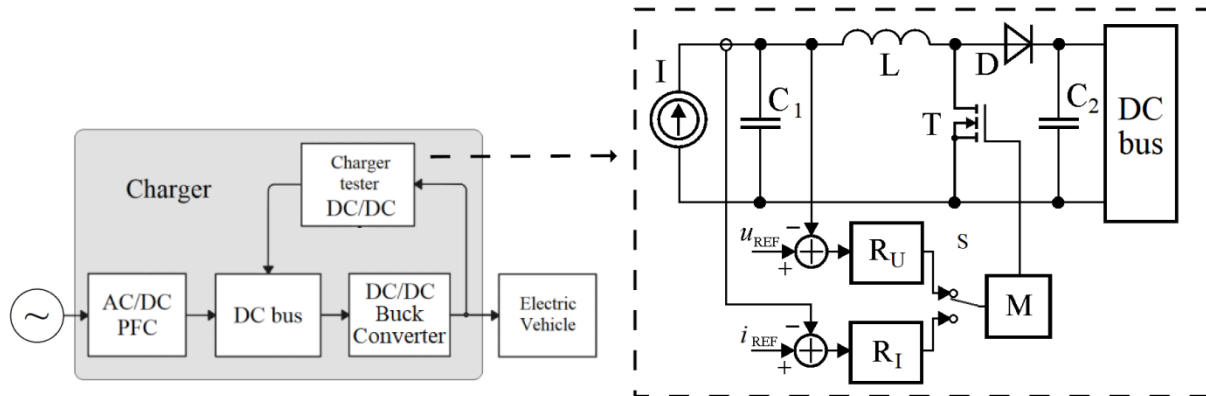


Figure 2. Block diagram of an electric vehicle charger with integrated SelfTest tester diagnostic functionality.

An electrochemical battery behaves as a voltage source; therefore, the tester is designed to maintain a programmable voltage level at its input, effectively emulating different battery states of charge. By dynamically adjusting this reference voltage, the tester can reproduce the characteristic CC/CV charging curve [55,56] and verify whether the charger follows the expected charging profile under controlled laboratory conditions. Tester therefore requires only voltage-loop control, however additional current protections are also necessary in the physical model. Entire energy is redirected to the DC bus of charger. Since energy circulates within the circuit and the converter powers itself, there is no risk of excessive voltage increase on the DC bus thus, eliminating the need to monitor the amount of energy transferred to it. In addition to operating as an active load, the tester can be extended to emulate selected BMS functions by generating programmable current and voltage reference profiles. This enables evaluation of the DC/DC control loops, including their dynamic response, stability and accuracy in following commanded charging profiles. Such functionality allows the tester to diagnose not only the power stage but also the control algorithm of the charger. Hardware wise, the charger tester can emulate various types of battery cells, and by modifying its control algorithms, it can reproduce

variations, and performing spectral analysis of the input current, to detect anomalies in the control circuitry or passive components [54]. The study focuses exclusively on the diagnostics of the power electronic converters used in the charger, along with the algorithms responsible for conditioning the output current and voltage, which together form the output stage ensuring correct battery charging and preventing damage during the charging process.

the characteristic behaviour of virtually any battery chemistry.

4. Simulation researches

4.1. Outputs voltage and current of an electric vehicle charger during SelfTest testing

The simulation model was developed using MATLAB/Simulink R2025a, employing the automatic solver selection feature, which automatically determines the solver type and configuration based on the model characteristics. This approach ensures numerical stability and reproducibility of results with minimal user intervention [57]. The conducted simulation research confirmed the correct operation of the SelfTest tester. In the developed model, it was possible to accurately reproduce both the desired charging current profile and the voltage waveform emulating the behaviour of a lithium-ion battery during a standard CC/CV charging process. The obtained results demonstrate that the implemented control algorithms respond properly to varying operating conditions and ensure stable interaction with the charger model.

A key aspect of the study was the precise generation of reference current and voltage values, which the tester must impose to reliably emulate the behaviour of a real battery. Proper definition of these reference signals directly affects

system stability and the quality of the resulting waveforms. Additionally, the research showed that adequate synchronization of the controllers and proper tuning of their dynamic parameters are essential to avoid undesired oscillations and to maintain correct operation of the entire charging path under simulation conditions. The simulation model employed PI controllers, whose parameters were tuned using the classical Ziegler–Nichols method, providing controller settings with appropriate dynamic response and closed-loop stability [58].

Table 1. List of the key electrical parameters and their values of the electric vehicle charger, considered in the simulation model.

Parameters	Symbols	Values
Power supply – the line voltage	U_L	230 V
Input power	P	12.5 kW
Rated efficiency of the system	η_{nom}	84.9%
Output current	I_{out}	25 A
Output voltage	U_{out}	420 V
Capacitor	C_1	1 mF / 600V
Inductor	L	100 uH / 30A
Switching frequency of the transistor (CCM)	f	20 kHz

Figure 3 shows the output voltage and current waveforms of the electric vehicle charger, obtained using the SelfTest tester.

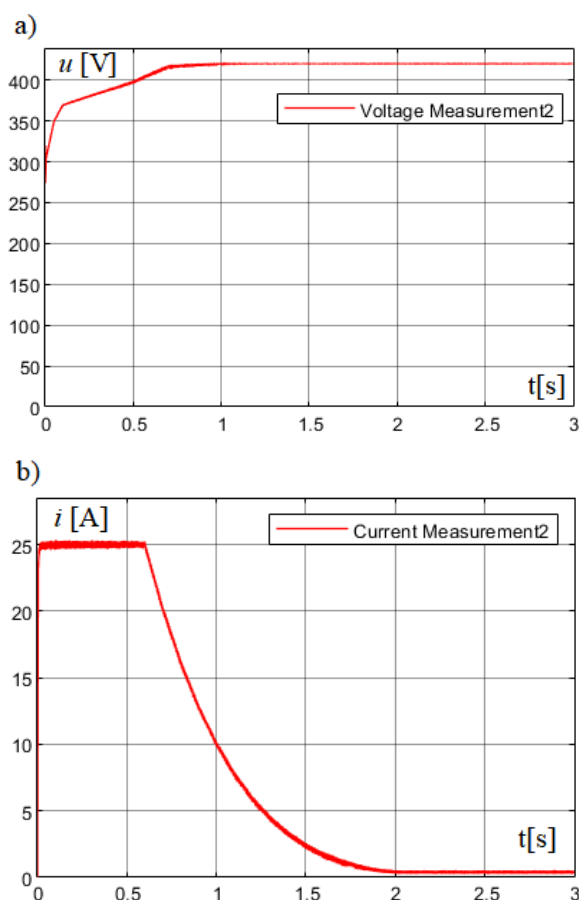


Figure 3. Charging curve of a 370 V lithium-ion battery for an electric vehicle, obtained using the SelfTest charger tester – simulation model: (a) charging voltage, (b) charging current.

The built simulation model was consistent with the block and schematic diagram shown in Figure 2. In Table 1 values of the key electrical parameters of the electric vehicle charger tester, considered in the simulation model.

4.2. Input current of an electric vehicle charger during SelfTest testing and Plug&Test with resistive load testing

The SelfTest tester enables substantial energy and cost savings, compared to Plug&Test tester with resistive load. A comparative overview of currents input waveform for both configurations is presented in Figure 4. Figure 4a depicts of Plug&Test tester with resistive load (see scheme in Figure 1c), and Figure 4b depicts of the SelfTest tester (see scheme in Figure 2). In the first scenario, the input current amplitude of charger reached 72.5 A, whereas in the second it was reduced to 2.1 A, resulting in a power decrease from 11.8 kW to 0.34 kW during test. Additionally, the SelfTest tester approach eliminates the need to dissipate large amounts of heat, thereby enhancing test safety and simplifying cooling requirements.

Despite the possibility of returning energy to the DC bus, the SelfTest tester generates losses resulting from parasitic circuit resistance and power losses in semiconductor elements. The main sources of energy losses in a circuit due to parasitic resistances and voltage drops are as follows:

- Charger transistor: $9/10 \cdot 0.2 \Omega \cdot (25 \text{ A})^2 = 112.5 \text{ W}$,
- Charger coil: $0.05 \Omega \cdot (25 \text{ A})^2 = 31.25 \text{ W}$,
- Charger diode: $1/10 \cdot 1.5 \text{ V} \cdot 25 \text{ A} = 3.75 \text{ W}$,
- Tester transistor: $1/10 \cdot 0.2 \Omega \cdot (25 \text{ A})^2 = 12.5 \text{ W}$,
- Tester coil: $0.05 \Omega \cdot (25 \text{ A})^2 = 31.25 \text{ W}$,
- Tester diode: $9/10 \cdot 1.5 \text{ V} \cdot 25 \text{ A} = 33.75 \text{ W}$,
- PFC transistor: $1/3 \cdot 0.2 \Omega \cdot (1.5 \text{ A})^2 = 0.15 \text{ W}$,
- PFC coil: $0.05 \Omega \cdot (1.5 \text{ A})^2 = 0.11 \text{ W}$,
- PFC diode: $2/3 \cdot 1.5 \text{ V} \cdot 1.5 \text{ A} = 1.5 \text{ W}$,
- Input bridge diodes: $2 \cdot 1.5 \text{ V} \cdot 1.5 \text{ A} = 4.5 \text{ W}$,
- Resistance of wire grid: $0.3 \Omega \cdot (1.5 \text{ A})^2 = 0.675 \text{ W}$.

In the present analysis, switching losses were included due to the adoption of a switching frequency of 20 kHz for tester circuit, 50kHz for output circuit of charger and 65kHz for PFC circuit of charger. The share of switching losses is significant but not dominant in these frequency ranges, especially in the case of SiC MOSFET transistors [59], which in recent years have increasingly replaced conventional silicon devices due to

their significantly reduced switching energy and superior high-frequency performance. Energy losses resulting from switching are difficult to calculate, as shown in the article [60]. However, the main sources of energy losses in the circuit resulting from switching power components are estimated based on parameters such as frequency, current, voltage and switching energy of semiconductor components, and are presented as follows in this paper:

- Charger transistor: about 20 W,
- Charger diode: about 20 W,
- Tester transistor: about 10 W,
- Tester diode: about 10 W,
- PFC transistor: about 5 W,
- PFC diode: about 5 W.

The total value of the most significant losses is almost 0.3 kW, which is consistent with the value of 0.34 kW obtained in the simulation model.

The discrepancy observed between the calculated and measured losses may therefore be partially attributed to the inaccurate calculations of switching losses in the analytical model, as well as losses in magnetic circuits related to the magnetization of the core.

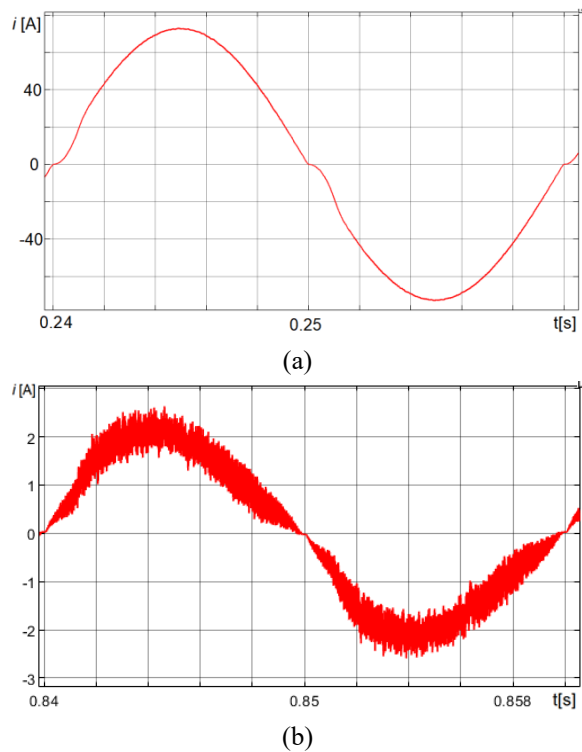


Figure 4. Input current waveform of the charger, using (a) Plug&Test tester with resistive load and (b) SelfTest tester.

The use of the SelfTest tester offers an additional benefit in

the form of significantly reduced impact on the power grid. This improvement stems not only from the lower active power consumption of the charger, but also from a marked reduction in magnitude of higher harmonics.

An important aspect of using a SelfTest tester is that the input current amplitude is never this low in any operating point of the charger. Therefore, during the design stage, the input current controllers must be anticipated and tuned such that the charger’s input converter remains stable also during the SelfTest procedure. This issue is critical for system stability, because unusually low input current amplitude may lead to reduced damping, increased susceptibility to oscillations, and undesirable transient behaviour. Consequently, the controller design must explicitly account for this special operating mode to ensure stable interaction between the charger and the tester. Table 2 presents a comparison of the key performance indicators of the Plug&Test and SelfTest testers. The mains current presented in Table 2 was measured directly from the simulation waveforms, whereas the estimated loss power was calculated based on Budean’s power theory [61] and the active-power formula, i.e., the product of current, voltage, and the cosine of the phase-shift angle between these quantities. However, the value of $\cos \varphi$ was assumed to be equal to one, because the apparent power was negligibly small. This simplification allows for approximate calculations whose purpose is only to illustrate the order of magnitude of the differences between the two methods.

Table 2. Comparative analysis of Plug&Test and SelfTest testers.

Category	Plug&Test tester (with resistive load)	SelfTest tester
Grid current amplitude	72.5 A	2.1 A
Heat dissipation requirements	Very high; requires large heatsinks, forced cooling, thermal safety measures	Minimal; no need to dissipate kilowatts of heat, improved safety
Total estimated losses	≈ 11.8 kW (entire load)	≈ 0.3 kW (consistent with 0.34 kW simulation)
Higher harmonics, for example the third harmonic amplitude	1.30 A	0.17 A
Control system behaviour	Stable tracking due to high current amplitude	Reduced tracking accuracy at very low current levels

4.3. Output voltage ripple of an electric vehicle charger during standard working and SelfTest testing

To compare the output voltage ripple of an electric vehicle charger, using SelfTest tester (see Figure 2) against the voltage across an electrochemical battery during charging, a simplified model of a lithium-ion electrochemical battery was developed [62,63]. The conceptual schematic of the simulation model is shown in Figure 10 in [62].

The capacitance of C (representing the energy stored in the battery) was determined, based on the electrical energy stored in the electrochemical battery, according to the following formula:

$$C[F] = \frac{2 Q[C] U_{BAT,nom}[V]}{(U_{BAT,max}[V] - E_{min}[V])^2} \quad (1)$$

where:

- E_{min} – minimum voltage of electromotive force (EMF) of the battery in a discharged state,
- $U_{BAT,max}$ – voltage of a fully charged battery at rest,
- Q – electric charge,
- $U_{BAT,nom}$ – nominal voltage of the battery.

For a lithium-ion electrochemical battery, with a capacity of 100 Ah and nominal voltage 370 V, the typical range of internal resistance R_s , is 0.1 m Ω to 0.3 m Ω . In the analyzed case, $R_s = 0.2$ m Ω was adopted [64]. The model also assumes a parallel resistance R_p , of around 1 M Ω . Table 3 presents the parameters of the components, used in the simulation model of the battery. Table 3. Parameters and their corresponding values, used in the electrochemical battery simulation model.

Parameters	Symbols	Values
Nominal voltage of battery	$U_{BAT,nom}$	370 V
Source voltage	E_{min}	300 V
Maximum voltage of battery	$U_{BAT,max}$	420 V
Series resistance in the model	R_s	0.2 m Ω
Parallel resistance in the model	R_p	1 M Ω
Capacitance in the model	C	18 500 F
Electric charge	Q	100 Ah

Figures 5 and 6 present the output voltage waveforms of the charger, corresponding to: the lithium-ion electrochemical battery model and the SelfTest tester, respectively.

Analysis of the output voltage waveforms of the charger revealed significant differences in oscillation characteristics, depending on the type of load. When loaded with the electrochemical battery model, only minimal oscillations were observed, with an magnitude of approximately 0.2 mV. Because values of the voltage ripples are in the range of mV, in practical

power electronic systems, dominated by measurement noise, the actual voltage oscillations at the battery terminals remain below the noise floor. The SelfTest tester produced the level of oscillations, reaching approximately 1.5 V. To mitigate the magnitude of these oscillations, it would be possible to employ capacitors with increased capacitance in the tester's structure. This modification could enhance the filtering properties of the system and improve its voltage stability. The issue of output voltage ripple should be evaluated individually; however, in the case under study, a ripple amplitude of approximately 1.5 V represents only 0.37% of the 400 V DC level. Such a low ripple is considered a very good result from the control system perspective. Nevertheless, this effect is desirable, because the output capacitance of the charger's power stage also influences the magnitude of these oscillations. Consequently, a loss of output capacitance will cause the oscillation amplitude to increase, providing a clear indication of a fault.

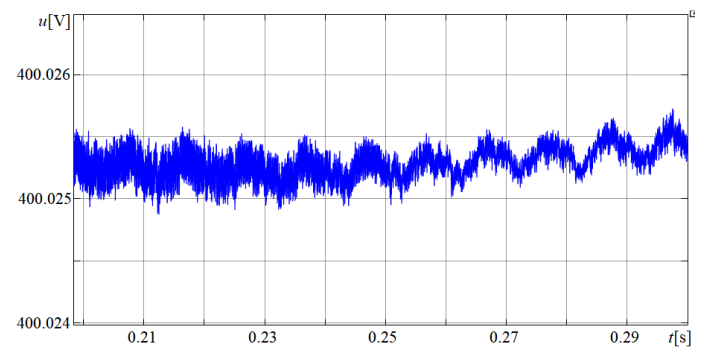


Figure 5. Output voltage waveform of the charger, under load with a lithium-ion electrochemical battery model.

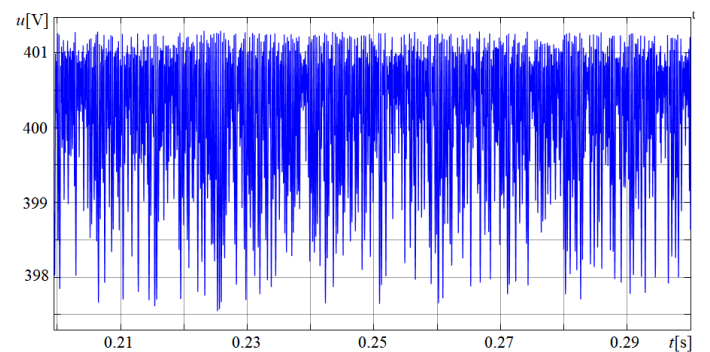


Figure 6. Output voltage waveform of the charger, under load with a SelfTest tester.

Moreover, in a real battery cell voltage oscillations may occur during the charging or discharging process. These oscillations can be attributed to the cell's complex physicochemical structure, transient phenomena occurring

within the electrode materials [65,66], as well as the presence of parasitic inductances and capacitances associated both with interconnection elements (e.g. wires) and other components of the system. The simplified battery model used in this study does not account for temperature dependent behaviour, aging effects, or nonlinearities in state of charge estimation under high current conditions. As a result, the diagnostic accuracy may be limited in scenarios involving dynamic load profiles or degraded cell performance. These effects were not replicated in the simulation model. Therefore, actual voltage oscillations, measured by the charger during the charging of a typical cell, may be significantly greater.

4.4. DC bus voltage of an electric vehicle charger during standard working and SelfTest testing

In the next step, the stability of the charger's DC bus voltage (see Figure 2) was evaluated, specifically between the PFC input stage and the charger's output stage. This aspect is particularly important because the energy delivered by the charger's output is redirected back to the DC bus. Figure 7 shows the DC bus voltage during standard charging operation, whereas Figure 8 presents the DC bus voltage during the operation of the SelfTest tester.

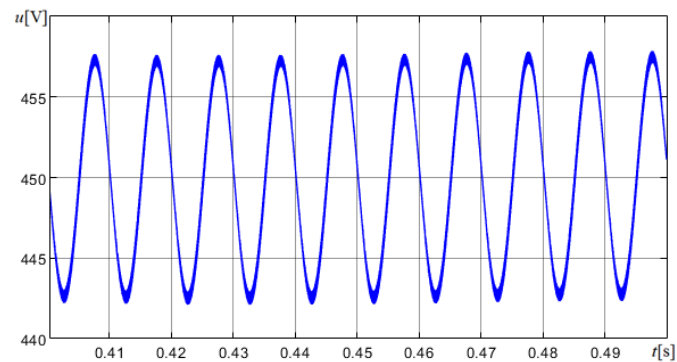


Figure 7. DC bus voltage waveform of the charger during standard charging operation.

The presented results indicate that when using the SelfTest tester, the DC bus voltage exhibits significantly improved stability, with notably reduced oscillations caused by the twice line frequency component. This effect primarily results from the fact that the power drawn from the grid in this operating mode is substantially lower.

Importantly, the SelfTest tester did not introduce any additional anomalies nor degrade the performance of the DC bus voltage regulation loop, implemented by the PFC stage

controllers responsible for stabilizing the DC bus voltage.

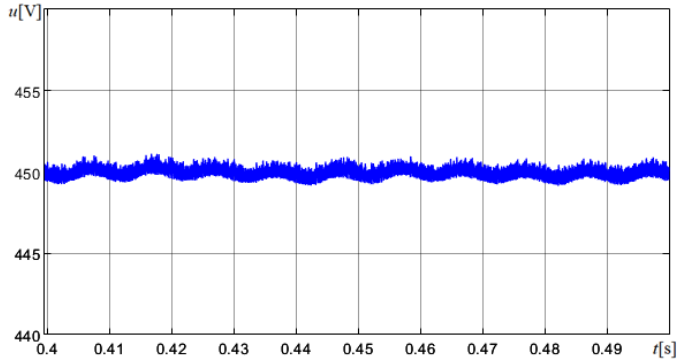


Figure 8. DC bus voltage waveform of the charger during SelfTest tester operation.

5. Diagnostic methods

Evaluation of EV charger performance using battery emulation and real charging scenarios is enhanced by a charger tester, which enables the implementation of the following diagnostic methods:

- **Simulation of battery related fault conditions,** including:
 - DC side short circuits allows detect:
 - an insufficiently rapid response of the overcurrent protection (OCP) circuitry,
 - an improper post short circuit restart.
 - Rapid voltage transients allows detect:
 - damaged or degraded output capacitors exhibiting elevated ESR.
- **Functional verification of protection mechanisms,** including:
 - Charger response to overvoltage and undervoltage battery conditions allows detect:
 - ineffective overvoltage protection (OVP) and undervoltage protection (UVP) protection mechanisms.
 - Validation of current and voltage limiting functions allows detect:
 - incorrect or unreliable voltage or current measurement.
- **Sustained full power operational testing,** including:
 - Evaluation of the thermal management system and its ability to dissipate heat under continuous maximum load allows detect:
 - insufficient thermal performance of heatsinks or

cooling fans,

- faulty or degraded temperature sensors (NTC or PTC).
- confirmation that the charger appropriately derates power output when thermal thresholds are exceeded.
- Analysis of charger behaviour under full load allows detect:
 - an increase in capacitor ESR under elevated temperature conditions,
 - improper operation of transistors or gate drivers under high temperature conditions.
- **Assessment of output voltage and current ripple,** allows detect:
 - degradation of output capacitors manifested by elevated ESR,
 - inductor damage, including inter turn short circuits,
 - insufficient inductance resulting from core saturation under load or elevated temperature
 - incorrect switching frequency, for example due to gate driver malfunction,
 - asymmetric operation of synchronous switching transistors,
 - damaged or degraded snubber circuit,
- **Verification of charging profile by:**
 - Emulation of battery state of charge (SoC) [67] can confirm:
 - verification of the charger's correct response as a function of the battery SoC.
 - Programmable enforcement of the charging profile, the tester provides Reconstruction of the CC/CV charging curve can confirm:
 - verification that the charger operates in accordance with the selected charging profile.
 - Battery recovery or reconditioning procedures can confirm:
 - assessment of the correct execution.

The diagnostic guidelines presented above are intentionally general and do not include specific limit values, waveforms, or parameter thresholds, as these are selected individually during the design process of each system.

Although the SelfTest tester concept significantly extends the diagnostic capabilities of the charger, it does not exclude the use of standard self-diagnostics performed by the charger itself or by the BMS. These diagnostic layers can operate in parallel, complementing one another. As a result, any potential limitations of the SelfTest procedure such as the absence of real battery electrochemical behaviour or the inability to observe long term degradation effects can be mitigated by the continuous monitoring and protection mechanisms inherent to conventional charger self-diagnostics and BMS-based supervision. Together, these approaches form a multi-level diagnostic framework that increases overall system reliability and safety.

However, the developed SelfTest tester concept introduces clear advantages compared to charger self-diagnosis and BMS based diagnostics:

- **Absence/failure of the BMS** – not all batteries are equipped with a BMS (e.g., traction lead-acid batteries), so the tester enables diagnostics even for such systems.
- **Ability to impose arbitrary operating conditions** – During normal operation, the charger adapts to the specific BMS of the connected battery and cannot impose arbitrary current levels, charging profiles, or dynamic load variations. In contrast, the tester can generate any desired current, voltage, or load transients, enabling the evaluation of extreme operating conditions that a vehicle would never produce. This makes it possible to detect faults that would remain hidden during standard charging. Additionally the load during charging battery is inherently dynamic and peak stress occurs only briefly during the CC to CV transition. Most hardware failures manifest under maximum electrical and thermal stress, while real batteries and BMS systems often limit current, masking potential charger defects.
- **Fast SelfTest before each charging test** – the tester can perform a quick self-test to verify correct charger operation and reduce the risk of battery damage in case of malfunction.
- **Diagnostics of individual DC/DC modules** – chargers are typically built from multiple DC/DC modules connected in parallel, which influence each other during operation. During parallel operation, these modules

influence each other, making it impossible to detect subtle faults in individual units, such as degraded output capacitors. The tester enables identification of weak, unstable, or faulty modules — something that cannot be achieved during battery charging.

- **Identification of abnormal ripple levels** – it would normally be suppressed by the large energy storage capacity of a real battery. Such measurements are critical for ensuring compliance with power quality requirements and preventing battery degradation
- **Testing without risk of battery degradation** – the

tester eliminates the risk of damaging the battery — the BMS always reacts after the hazardous condition has already occurred, which may contribute to cell degradation.

- **Full repeatability of tests** – each vehicle has a battery with a different level of degradation, which affects the charging curve and voltage characteristics. The tester eliminates this variability, enabling consistent and comparable diagnostic results.

Table 4 presents a summary of the characteristics of the analyzed diagnostic methods for electric vehicle chargers.

Table 4. Summary of features of various diagnostic methods.

Approach / Feature	Using BMS	Plug&Test Tester	SelfTest Tester
Battery diagnostics without BMS	Impossible	Possible	Possible
Arbitrary working conditions	no possibility of forcing	Possible	Possible
Fault detection under maximum stress	Possible to a limited extent	Possible without limits	Possible without limits
Quick self-test before charging	Impossible	Impossible	Possible
DC/DC module diagnostics	Impossible	Impossible	Possible
Ripple and power quality measurement at the output	Impossible	Possible	Possible
Test repeatability	Depends on battery usage	High repeatability	High repeatability
Diagnostic time and costs	Low	High	Low

6. Preliminary laboratory research

6.1. Plug&Test tester with resistive load

Preliminary laboratory tests were carried out as part of the conducted work. In these tests, the Plug&Test tester prototype was used. The laboratory experiment was performed on a low-power 12 V charger intended for small vehicles equipped with lead-acid batteries up to 100 Ah. This setup was selected for safety reasons and to enable controlled preliminary validation of the Plug&Test concept and testing the control section. Although the test does not reach the kW-level power typical for passenger EV chargers, it represents real operating conditions of an actual charging device. The aim of this stage was to reproduce the charging curve and evaluate its boundary parameters under safe laboratory conditions and to test the selected structure of the control part of the charger tester. Full-scale validation on multi-kilowatt chargers requires dedicated infrastructure and will be carried out in future work. The schematic of the laboratory setup is shown in Fig. 9, and the photograph of the setup is presented in Fig. 10. The test bench was built using an Infineon evaluation board [68] with IFX007T [69], modified by the authors to implement a DC/DC

boost converter and to enable current and voltage measurements at the charger output. As a control unit an Microchip evaluation board [70] was used with ATmega328P [71].

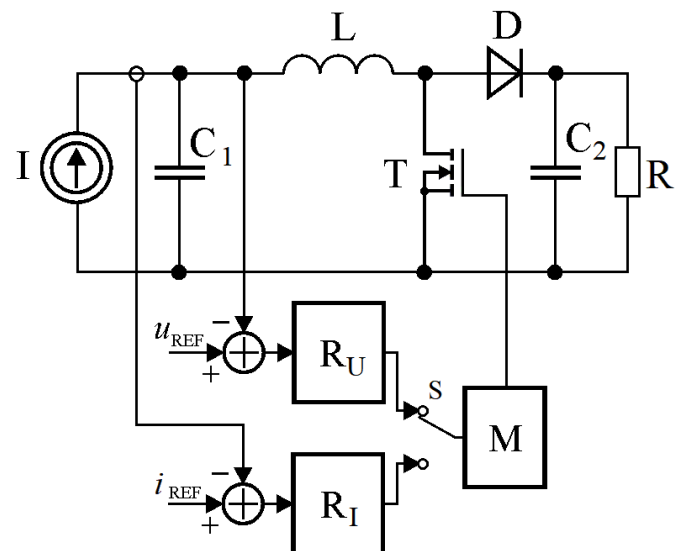


Figure 9. The schematic of the laboratory setup.

Battery chargers are typically designed such that their output exhibits a current source characteristic, which results from the requirement to precisely control the charging current. Therefore, the charger should be considered a current source, as illustrated in Fig. 9, where a current source I is placed at the input.

The operating principle of the system is as follows. The setup is equipped with two controllers: R_I and R_U . Since the system must emulate the behaviour of a real traction battery, the role of controller R_U is to impose the appropriate output voltage of the charger so as to reproduce the charging process during the CC phase. The reference signal u_{ref} should follow the theoretical voltage profile of the specific battery type during this phase.

Controller R_I , in turn, is responsible for shaping the output current in such a way that the resulting current waveform shape corresponds to the charging current in the CV phase. The R_I regulator is able to force a given current value by changing the load while maintaining a constant output voltage. Consequently, the reference signal i_{ref} should follow the theoretical current profile for the CV phase; the method for determining this waveform shape is discussed in [62]. Depending on which charging phase is being tested, the switch S selects the appropriate controller.

Next, the block M acts as a modulator whose task is to convert the controller's output signal into a corresponding rectangular waveform used to drive the transistor. This is a classic modulator that compares the output signal of the regulator with a saw tooth signal.

The Plug&Test prototype was connected to a resistive load, which served as the output burden for the charger. The resistance value had to be carefully selected to ensure that the tester could reproduce the characteristic charging curve at the charger input while simultaneously maintaining realistic voltage and current levels at its output. If the resistance were too low, the tester would draw excessive current and fail to generate the required input-current profile. Conversely, if the resistance were too high, the output voltage of the tester could increase to unsafe levels. Therefore, the chosen resistance represents a compromise that enables stable reproduction of the charging waveform while keeping the operating point within the safe limits of the laboratory setup.

The power electronics converter, used in the tester, must be additionally equipped with the capacitor C_1 , serving as a temporary energy buffer, which is essential for maintaining a stable energy flow. Capacitor C_2 stabilizes the operation of the entire system and ensures proper dynamic behaviour.

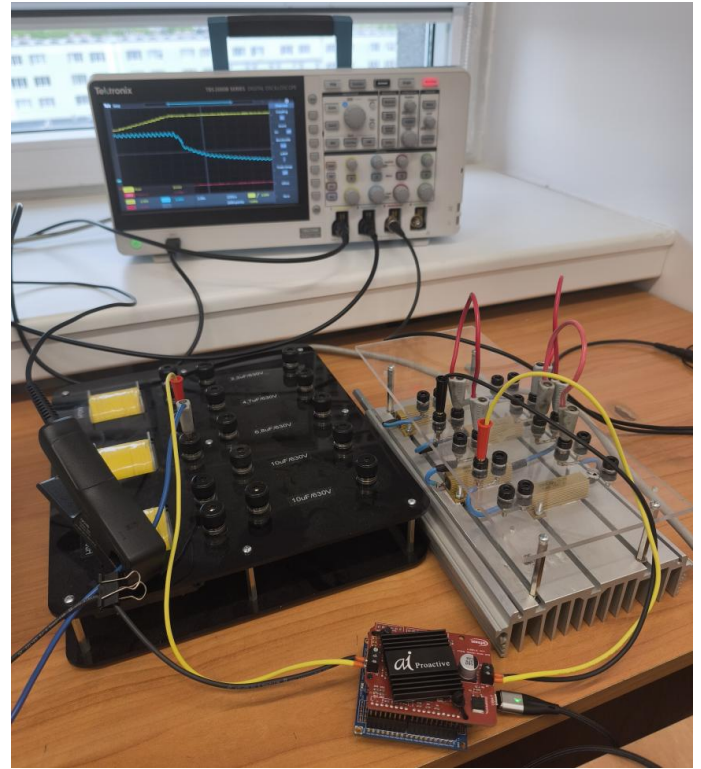


Figure 10. The photograph of the laboratory setup.

The objective of the experiment was to verify whether the charger follows the correct CC/CV charging profile. Figure 11 presents the measured output current and voltage waveforms. The vertical scale was set to: (a) blue trace – output current, 1 A/div; (b) yellow trace – output voltage, 2 V/div in Figures 11 and 12. The horizontal scale was set to 0.1 s/div in Figure 11 and 1 s/div in Fig. 12.

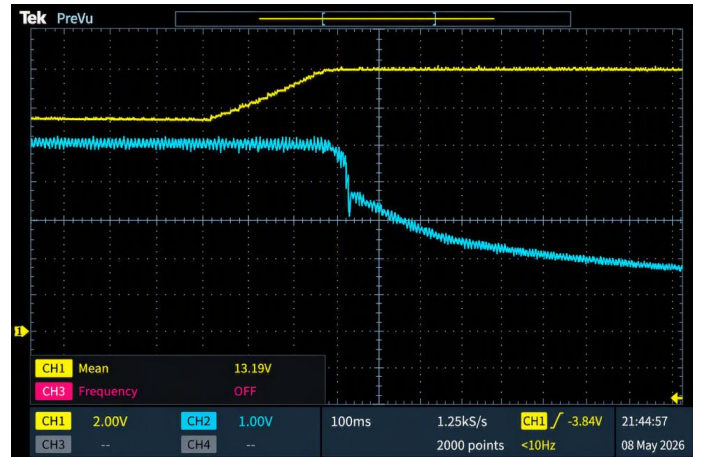


Figure 11. Measured output current and voltage waveforms; total test duration: 1.3 second.

The obtained waveforms confirm the correct operation of both the charger and the Plug&Test tester, supporting the research hypothesis and enabling further development of more advanced charger testers. Based on the obtained waveforms, it

can be seen that the charger correctly maintains a constant current in the CC phase, not exceeding the maximum charging current, which in this application was 5 A, and correctly reduces the current in the CV phase so as not to exceed the maximum battery voltage, which was 14.2 V. However, a small disturbance in the current waveform can be observed during the transition from CC to CV mode. This effect may be caused by an excessively rapid current decay, which does not occur under real battery-charging conditions or mismatch of operating points/interference between the charger converter and the tester converter. In addition, there is a possibility that the microcontroller used in the Plug&Test prototype provides insufficient PWM resolution for driving the transistors in the tester's power stage. Limited PWM resolution can lead to small but noticeable perturbations in the current and voltage waveforms during rapid transitions. This fact requires more detailed study and will be taken into account in further experimental studies.

To improve the completeness of the experimental section, an additional laboratory test was performed, and the measurement duration was extended from 1.3 s to 13 s, as shown in Figure 12. This longer acquisition window allows for a clearer observation of the transient behaviour of the charger under controlled load conditions.

Although the waveforms in Figure 12 appear to exhibit different pulsation frequencies compared to Figure 11, this effect results probably from sampling limitations associated with the Nyquist criterion [72,73] and the large measurement window used during oscilloscope acquisition. When the sampling frequency is insufficient relative to the highest frequency component of the signal, aliasing effects may occur, leading to an apparent change in pulsation frequency. In such cases, a dedicated high-speed data recorder with appropriate sampling bandwidth would be required to capture the waveform without loss of information, for example [74]. This limitation is inherent to oscilloscope-based acquisition over extended time windows and does not reflect the actual behaviour of the charger or the tester.

Although the experimental studies presented here were conducted on a low-voltage prototype, their goal was to validate the diagnostic concept and fault detection mechanisms in laboratory conditions. The prototype implements the simplest

version of the Plug&Test tester with a resistive load, which enabled the evaluation of load profile generation without the need for high-power infrastructure.

Future work includes experimental verification at real high-power charging stations, including high-load tests, diagnostics of parallel DC/DC modules, and assessment of compliance with power quality requirements. The results of these studies will be presented in a subsequent publication.



Figure 12. Measured output current and voltage waveforms; total test duration: 13 second.

7. Discussion

This work presents the fundamental research and laboratory-level validation of the SelfTest diagnostic concept. Quantitative evaluation of diagnostic accuracy, repeatability, sensitivity, long-term reliability, and cost-effectiveness requires extensive field measurements, fault-injection experiments, and operational data from commercial charging stations. These application-oriented analyses, including implementation costs, scalability, and integration with existing infrastructure, will be addressed in future stages of the SelfTest development.

The present study therefore serves as a conceptual and simulation-based foundation. The diagnostic functionalities discussed in the manuscript are treated as potential capabilities of the architecture rather than experimentally validated metrics. The primary evaluation criterion is the accurate reproduction of the charging curve and the assessment of its boundary parameters under controlled simulation conditions. Full quantitative validation and industrial implementation analysis will be carried out in subsequent work.

8. Conclusions

In this work, a review of current diagnostic methods for electric

vehicle chargers was conducted. An original SelfTest concept was proposed, aimed at enabling internal evaluation of charger operation without external instrumentation. Simulation studies were performed to analyze the charging-curve behaviour and the difference in voltage conditioning relative to a simulated battery model. The battery was represented by a simplified simulation model that does not include temperature effects, aging, or real electrochemical behaviour; therefore, the obtained results may be subject to significant error. Finally, preliminary experimental tests were carried out at a safe voltage level due to laboratory safety considerations. These tests confirmed the feasibility of the proposed diagnostic approach under controlled low-power conditions.

An advantage of using a diagnostic tester, compared to analysing charging curves with an electrochemical battery, is the clarity of diagnosis. In tests, involving a real electrochemical battery, it is not always certain, whether detected deviations stem from battery faults [75–77] or charger malfunction. In contrast, when using a tester, any irregularities directly indicate the need for technical intervention, as potential faults, are limited to the tester or the charger itself.

Another benefit of the tester is the ability to configure a constant power draw, enabling more precise and repeatable testing. This is not feasible with electrochemical batteries, whose energy demand varies throughout the charging process. This aspect plays a crucial role in EMC testing of the charger, significantly accelerating analysis across all operating points [78–80].

An additional advantage is the service efficiency of the tester, which allows rapid diagnostics of the charging station without the need to connect a real electric vehicle. This approach

shortens fault identification time and eliminates the need to involve an actual electrochemical battery. This makes it possible to carry out regular technical inspections of the charging stations, improving infrastructure availability for end users.

Although the presented diagnostic methods for EV charging stations offer numerous benefits, their implementation also involves certain technical and operational risks and responsibilities, such as:

- possible discrepancies from real charging profiles – testers may not replicate variable conditions typical of different battery types,
- potential tester malfunctions – errors may lead to incorrect diagnoses,
- calibration requirements – to ensure reliable results, the tester must be regularly calibrated and certified.

In addition to these qualitative advantages, the presented solution also offers a number of practical, potentially quantitative benefits. These include the ability to enforce fully repeatable load conditions, reduced EMC analysis time thanks to constant power consumption, clearer diagnosis due to the elimination of the influence of the actual battery, and increased service efficiency due to the elimination of the need to connect the vehicle. Future work plans include a quantitative assessment of these parameters at commercial charging stations.

This study considers two main approaches: an external tester operated by a service technician, and a tester integrated into the charging station, performing tests automatically. Both solutions have potential applications. The first one offers flexibility and mobility, while the second one enables autonomous monitoring of the charger's technical condition.

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