

Article

Distributed V2G-Enabled Multiport DC Charging System with Hierarchical Charging Management Strategy[†]

Shahid Jaman^{1,2,*}, Amin Dalir^{1,2} , Thomas Geury^{1,2} , Mohamed El-Baghdadi^{1,2}  and Omar Hegazy^{1,2,*} 

¹ MOBI-EPOWERS Research Group, ETEC Department, Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussels, Belgium; amin.dalir@vub.be (A.D.); thomas.geury@vub.be (T.G.); mohamed.el.baghdadi@vub.be (M.E.-B.)

² Flanders Make, Gaston Geenslaan 8, 3001 Heverlee, Belgium

* Correspondence: shahid.jaman@vub.be (S.J.); omar.hegazy@vub.be (O.H.)

[†] This article is a revised and expanded version of a paper entitled Interoperable Multiport DC Charging System with Optimal Charging Management Strategy for Electric Vehicle Fleet Charging Hub, which was presented at EVS38, Gothenburg, 18 June 2025.

Abstract

This paper presents a distributed V2G-enabled multiport DC charging system with a hierarchical charging management strategy. Unlike conventional architectures based on centralized power converter cabinets, the proposed system distributes bidirectional power converters within individual multiport dispensers, each equipped with a local charging power management device. This architecture improves system scalability, fault tolerance, and operational flexibility while enabling vehicle-level charging and V2G services. A hierarchical control framework is introduced, consisting of high-level optimal charging scheduling, mid-level power coordination among distributed dispensers, and low-level converter control. Key elements include modular power units that can be dynamically configured and expanded, providing a cost-effective and adaptable solution for growing EV markets. Experimental results obtained from a 45 kW modular DC charging prototype demonstrate an efficiency improvement of up to 2% at rated power compared to a non-modular charger. In contrast, the optimized charging strategy achieves an overall charging cost reduction of approximately 11% and a peak load demand reduction of up to 31%. Furthermore, stable bidirectional power flow, effective power sharing, and total harmonic distortion within regulatory limits are experimentally validated during both charging and V2G operation. The prototype is implemented to validate the proposed charging system in the laboratory environment.

Keywords: electric vehicles; DC charging technology; charging management; Vehicle-to-Grid (V2G)



Academic Editor: Michael Fowler

Received: 24 February 2026

Revised: 24 March 2026

Accepted: 6 April 2026

Published: 10 April 2026

Copyright: © 2026 by the authors.

Published by MDPI on behalf of the

World Electric Vehicle Association.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The rapid advancement of EV technology has paved the way for a new era of transportation characterized by sustainability and innovation. As the demand for EVs continues to rise globally, the development of robust charging infrastructure with V2G systems is paramount to support the widespread adoption and maximize the benefits of electrified mobility. According to [1], 6.8 million public and 29.4 million private charging points are planned to be installed by 2030 in the EU region for both urban and rural areas. It is key to ensure equitable access to e-Mobility, and its benefits, for all: Today, 75% of the European population lives in cities and urban areas [2], and more than 40% of car owners

have no access to off-street/private parking [3], so they cannot install home EV chargers. If these people cannot access on-street charging infrastructure for daily charging, then the EU will not achieve the targets for EV uptake and electrification of transport settled by the Sustainable and Smart Mobility Strategy, FitFor55 and AFIR. In addition, today, households without off-street parking have more limited options for accessing smart charging, for example, those living in flats or rental properties [4]. Thus, there is an urgent need for innovative and diverse charging solutions for large-scale deployment in urban areas.

The hybrid charging ecosystem combining traditional AC charging and low-power DC charging systems is emerging as a practical and cost-effective solution in dense urban areas, where space constraints, grid limitations, and high vehicle concentration coexist [5–8]. Conventional AC charging infrastructure (typically 3.3–22 kW) remains widely adopted due to its lower installation cost and compatibility with existing grid infrastructure [9–11]. However, AC charging is often limited by onboard charger ratings, resulting in longer charging times and reduced flexibility for fleet operations and high-utilization scenarios. On the other hand, the DC fast charger (typically > 150 kW) installed in commercial or industrial parking lots includes a large power converter cabinet, as shown in Figure 1, but is not easily accessible for the people of residential areas.

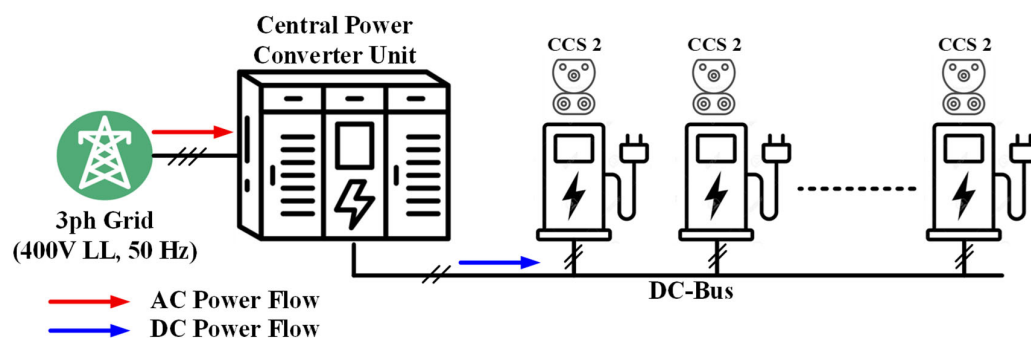


Figure 1. Typical multiport charging hub with centralized power converter unit for different applications and services [5].

The fast charging system is also not suitable for the large-scale deployment in residential areas due to higher cost, space, and grid limitation issues [12–14]. Thus, there is a need for an innovative DC charging system, which is not only suitable for large-scale deployment in residential areas but also reduces the charging cost by using bidirectionality and smart charging features. To complement commercial fast charging facilities, low-power DC charging systems (typically 20–100 kW) are gaining increasing attention for urban and semi-public applications. Unlike high-power fast chargers, low-power DC systems provide a balanced trade-off between infrastructure cost, charging speed, and grid impact. The charging infrastructure experts have already developed low-power DC charger solutions for urban area installations.

Recent studies on EV charging infrastructure have explored diverse architectures and control strategies to improve scalability and grid integration. A modular multiport DC fast charger supported by a reconfigurable battery system, enhancing grid flexibility, has been proposed in [15], but focusing on fast charging rather than low-power distributed deployment. Reference [16] introduced a multiport DC–DC converter with differential power processing, improving efficiency at the converter level, yet lacking system-level scalability and coordinated energy management. Similarly, ref. [17] developed a bidirectional DC–DC converter for EV charging in DC grids, but the work remains converter-centric without extending to multiport charging infrastructure. From a control perspective, ref. [18] addressed centralized charging optimization for EV fleets, demonstrating effective scheduling but lacking modular hardware design and distributed architectures. Additionally, the

optimized charging process is validated using 50 kW single-power-module-based EVSE hardware. In addition, ref. [19] investigated modular charging concepts for ultra-fast stations; however, their work is simulation-based and not tailored to low-power urban deployment. Low-power PV-based charging solutions have been demonstrated in [20] with bidirectional capability but remain limited to small-scale prototypes. The summary of the literature related to DC charging systems is listed in Table 1 below and compared with the proposed DC charging system.

Table 1. The state of the art for recent DC charging system research.

Ref.	Architecture	Dispenser Control	Power Level	Bidirectionality	Validation	PE Converter—Disp. Integration
[15]	BESS-based dedicated DC/DC per port	Current mode low level	*N/A	Yes	Lab Prototype	No
[16]	Dedicated DC/DC per port	Phase-shift low level	*N/A	Yes	Lab Prototype	No
[17]	Dedicated ML DC/DC per port	CC-CV based low level	*N/A	Yes	Lab Prototype	No
[18]	Single AC/DC per port	CC-CV with Optimized Current Control	45–50 kW	No	Lab Prototype	Yes
[19]	Dedicated DC/DC per port	CC-CV with module logic control	50 kW	No	Simulation	No
[20]	Single AC/DC per port	Converter centric mode specific	2 kW	Yes	Lab Prototype	No
Proposed	Modular AC/DC per port	Hierarchical multilevel control	45 kW	Yes	Lab prototype	Yes

*N/A: Not Available.

To address the challenges regarding large-scale deployment, space availability in urban residential areas, and higher installation cost for fast DC charging station, this paper proposes a distributed modular multiport DC charging system (2 CCS ports per dispenser) integrated with PE converters tailored for EV fleet charging hubs, as shown in Figure 2.

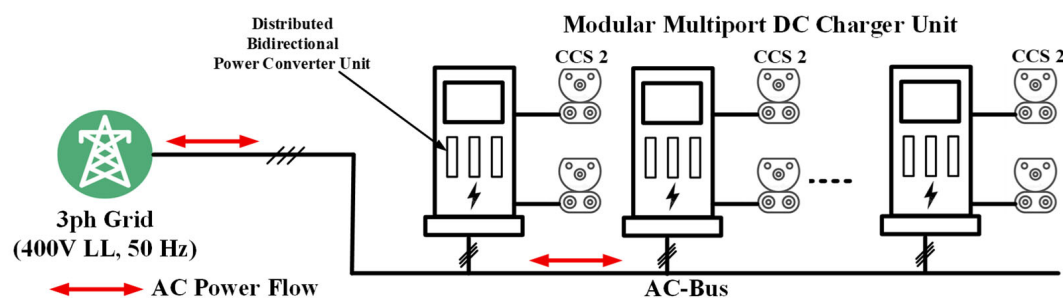


Figure 2. Multiport charging hub with a distributed power converter unit for different applications and services.

The primary novelty lies in the integration of a distributed bidirectional PE converter-based multiport DC dispenser topology with an embedded hierarchical charging management system. The proposed system operation is validated through laboratory experiments and real urban charging site operation. The proposed architecture supports bidirectional power flow, distributed scalable hardware modules, and intelligent scheduling algorithms that dynamically allocate power based on vehicle priority, SoC, and departure time. The

interoperability is ensured through compliance with established communication standards and adaptive control protocols. Experimental validation on a 45 kW prototype demonstrates high system efficiency (>95%), controlled THD, and effective power distribution across ports. The proposed solution addresses key technical and operational challenges in EV fleet electrification and offers a path toward reliable, grid-supportive, and cost-effective fleet charging infrastructures.

2. Proposed Multiport Charging Station Using Module Integrated Dispenser

The proposed low-power modular charging system is shown in Figure 3. The detailed system description is discussed below. The proposed modular charging solution comprises two containers, each of which supplies two charging ports. Each charger container contains a 3×15 kW AC/DC converter. The charging station consists of two groups of power converters. The AC/DC converter group has a 3×15 kW modular structure to serve the charging power to the L3e (passenger cars/vans) and emulate a scaled charging system.

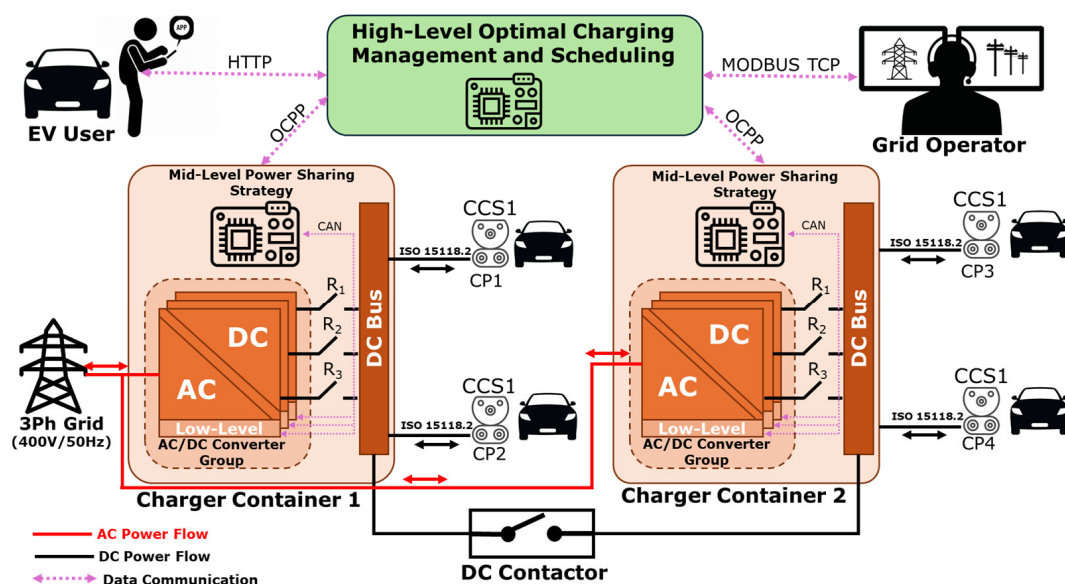


Figure 3. Proposed modular multiport charging station layout including interoperable communication protocols.

The charging system comprises two containers, each equipped with two ports. This configuration allows up to four electric vehicles to charge concurrently at a baseline rate of 22.5 kW per port. The station features dynamic power scaling based on port availability, facilitated by the parallel connection of power electronic converters via a DC relay. Through this power-sharing architecture, the system can dynamically allocate output, such as delivering 45 kW to two vehicles simultaneously or routing the maximum 90 kW capacity to a single vehicle if all other ports are unoccupied. To execute this high-power charging, a dedicated power-sharing strategy governs the activation of the AC/DC module contactors (R_x , where x represents the number of required active modules).

The mid-level module power-sharing controller allocates the reference power (P_{ref}) signal, which comes from the high-level optimum charging scheduler. The core function of the charging scheduler is to generate the required power reference to optimize the charging cost. To perform this optimization, the high-level charging scheduler required the external signal such as forecasted electricity price (€/kWh), EV user information (arrival time, departure time, initial SoC, Slow/Fast Charging), EV battery information (battery capacity, SoC status), total charging load demand, etc. The required charging power profile

is generated via a convex optimization algorithm, which is transmitted to the mid-level power-sharing algorithm to allocate the power among the modules.

3. Hierarchical Charging Power Management and Control Strategy

The multilevel charging station management and control strategy is shown in Figure 4, which is considered for the proposed hybrid charging station. The levels are high-level, mid-level, and low-level. The high-level aim is to introduce intelligence in the whole microgrid, as discussed in the above sections, so that an optimal operation for the charging station can be achieved. The high-level management strategy employs a convex optimization-based charging scheduler to minimize charging cost while satisfying EV and grid constraints. At this level, forecasted electricity price, EV user requirements, battery state, and site load information are processed to generate the charging power references for the lower control layers.

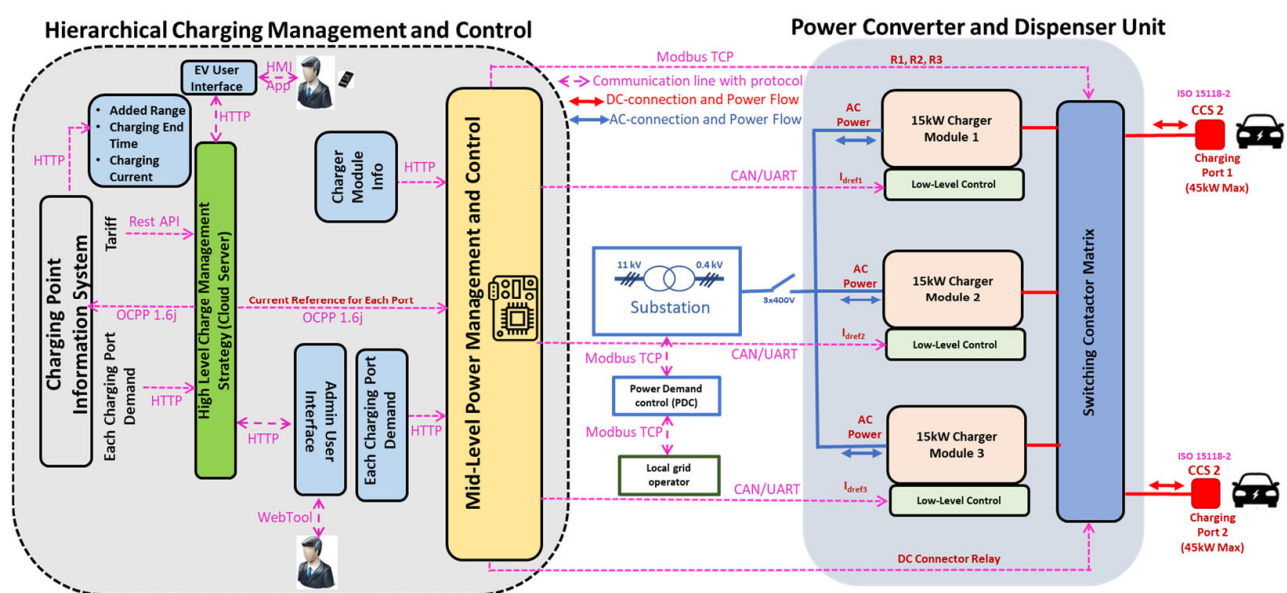


Figure 4. Block diagram of hierarchical charging management and power flow control strategy, including communication and control signals for the charging container.

This hierarchical structure is delineated by distinct response times and operational objectives. Firstly, the high-level management layer exhibits the slowest regulation dynamics, which operates across time intervals ranging from seconds to hours. The primary function is to optimize user charging costs by generating the required current references for individual load requests. Secondly, mid-level control operates above the local controllers to govern the power flow and power quality. This layer features a moderate response time of 100 ms–1 s and is responsible for adjusting voltage, current, or frequency deviations introduced by the lower tiers within the master station's power electronic converters. Lastly, the low-level control layer manages the local power, voltage, and current loops, ensuring the stable operation of each power converter. This layer possesses the most rapid response dynamics, functioning within 1–10 ms, which allows it supply.

3.1. High-Level Charging Management Strategy (HL-CMS)

In contrast to heuristic approaches such as genetic algorithms reported in the prior literature, the high-level CMS adopted in this work is implemented using convex optimization. This choice ensures computational tractability, repeatability, and efficient real-time scheduling under linear constraints. The convex optimization strategy is utilized to generate the

charging current profile from a high-level charging management block by optimizing the charging cost. The optimization algorithm aims to minimize the charging cost for the EV operator, while satisfying the requirements and constraints of the EV and grid operators. The HL-CMS is adopted using convex optimization in this research work, which applies to charging stations. The strategy initiates upon the arrival of the EV at the charging station. When an EV arrives at a charging station, the driver informs the EVSE of their needs. The charge request is received by the HL-CMS, which then performs the real-time scheduling and optimization algorithm [16]. The scheduling of the EV charging process is deemed difficult due to the wide range of limitations imposed by many parties. This makes it challenging to develop charging schedules that are viable, efficient, and acceptable to all stakeholders, especially when numerous EVs must be charged at the same time. The detailed explanation of the mathematical formulation for the optimization problem is out of scope for this paper. Mathematically, the optimization problem is formulated from Equation (1) to Equation (5) as follows:

$$\text{Minimize} \left(\sum_{i \in N} \left(\beta_0 y_i + \frac{\beta_1}{2} y_i^2 \right) \right) - \left(\beta_0 P_i^b + \frac{\beta_1}{2} (P_i^b)^2 \right) \quad (1)$$

$$\begin{aligned} &\text{Subject to} \\ &y_i = P_i^b + \sum_{m \in M} p_{mi} S_{mi}, \quad \forall i \in N \end{aligned} \quad (2)$$

$$0 \leq \text{SoC}_m^{\text{ini}} + \sum_{i \in N} i p_{mi} S_{mi} \leq \text{SoC}_m^{\text{max}}, \quad \forall i \in N, \quad \forall m \in M \quad (3)$$

$$\text{SoC}_m^{\text{ini}} + \sum_{i \in N} i p_{mi} S_{mi} \geq \alpha_m \text{SoC}_m^{\text{max}}, \quad \forall i \in N, \quad \forall m \in M \quad (4)$$

$$0 \leq p_{mi} \leq P_{\text{max}}^{\text{ch}}, \quad \forall i \in N, \quad \forall m \in M \quad (5)$$

The parameters β_0 and β_1 denote non-negative coefficients representing the intercept (€/kWh) and slope (€/kWh/kW) within the adopted pricing formulation. Since all constraint expressions are linear, the resulting formulation constitutes a convex optimization problem, which can be efficiently solved using interior-point algorithms [17]. The variable N indicates the total number of time intervals considered, typically spanning 24 h with each interval having a duration of $i = 1$ h. The set M corresponds to the total number of electric vehicles (EVs) participating in the system, specifically those scheduled for charging. During the computation process, each EV is sequentially indexed using m . The aggregate site power demand which denoted by y_i , incorporates both the base load $P_{b,i}$ and the EV charging demand. The charging schedule matrix S_{mi} is derived from user-provided charging requirements and is used to represent the expected charging periods for each EV. The battery energy constraints are defined by the minimum and maximum state of charge limits, $\text{SoC}_m^{\text{min}}$ and $\text{SoC}_m^{\text{max}}$, respectively, expressed in kWh. Furthermore, the charging power assigned to each EV is represented by p_{mi} , which is bounded above by the maximum allowable charging rate p_{max} during the optimization process.

3.2. Mid-Level Power Management Strategy

The mid-level control layer is responsible for power coordination and module-level management within the charging station.

The implementation strategy is adapted from [21] include module activation/deactivation, current reference allocation, and power flow regulation between the AC/DC conversion stage and the EV charging ports as shown in Figure 5. This layer operates on a slower timescale compared to the converter control loops, ensuring proper hierarchical separation. The total reference charging current, $I_{d,\text{tot}}^{\text{ref}}$, produced by the supervisory control layer is used as the

primary input to the system. Based on this required current and the rated current capacity of each module, the controller determines the number of modules that must be activated, denoted as N_{active} , as expressed in Equation (6). Subsequently, considering the physical arrangement and availability of modules, the system selects the appropriate modules for operation. When the system operates in steady-state conditions, the reference d-axis current for each active module is computed by equally distributing the total reference current among the active modules, as defined in Equation (7).

$$N_{active} = \frac{I_d^{ref\ tot}}{I_d^{rated}} \quad (6)$$

$$I_{d1\dots n}^{ref} = \frac{I_d^{ref\ tot}}{N_{active}} \quad (7)$$

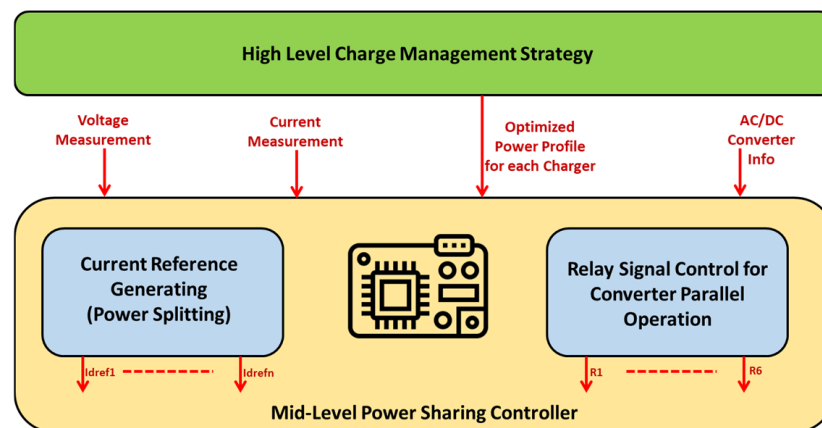


Figure 5. Mid-level charging management and control interlinked with HL-CMS.

To prevent frequent switching and ensure system stability, a hysteresis-based activation mechanism is implemented. Specifically, module activation and deactivation thresholds are defined as Equations (8) and (9):

$$\text{Activation threshold, } I_d^{ref\ tot} > N_{active} \times I_d^{rated} + \Delta I_d^{up} \quad (8)$$

$$\text{Deactivation threshold, } I_d^{ref\ tot} < N_{active} \times I_d^{rated} + \Delta I_d^{down} \quad (9)$$

where ΔI_d^{up} and ΔI_d^{down} represent hysteresis margins. The mid-level controller is implemented on a RaspberryPi device with a certain control update rate (1–10 Hz), which is sufficiently slower than the converter switching dynamics but fast enough to respond to load variations. Additionally, relay switching delays and interlocking constraints are incorporated to avoid simultaneous switching events and ensure safe operation.

3.3. Low-Level Control Strategy

This control layer governs the local operation of each power converter module, ensuring accurate current tracking, voltage regulation, and stable bidirectional power flow. This layer operates at the fastest timescale in the system, typically in the sample time range of [50–100 μ s]. The low-level converter employs a dual-loop control structure, consisting of inner current control loop and outer DC-link voltage control loop.

The current reference (I_{d1}^{ref}) for the inner current control loop is primarily generated by the mid-level charging management layer. The outer DC-link voltage controller provides a secondary limiting reference (I_{dref}^{dc}) to ensure DC-link stability. The final current reference (I_d^{ref}) is selected through a supervisory constraint to guarantee both charging performance

and system stability. The PI can compensate for the current error (difference between setpoint and measurement) and generate the control signals, as shown in Figure 6. The PI controller gain selection strategy for AC/DC converters is described in [22]. Then, this control signal (v_{abc}^c) is compared with the carrier signal to produce suitable switching patterns for the PE converter. The phase-locked loop (PLL) is used to determine the phase angle, θ , for the inverse park transformation. To improve current tracking performance and decouple the d-q axis dynamics, feedforward decoupling terms $-\omega L i_q$ and $+\omega L i_d$ are included in the current control loop. This allows independent regulation of active and reactive current components and enhances dynamic response under varying operating conditions.

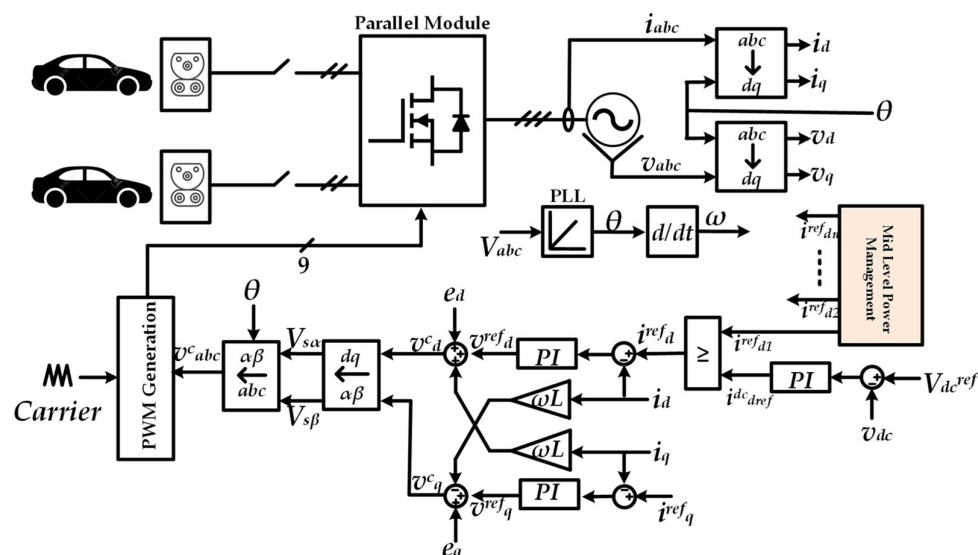


Figure 6. Dual-loop control strategy to generate PWM signal to drive the power converter unit.

4. Results and Discussions

This section presents the performance evaluation of the proposed modular low-power DC charging system through both simulation and experimental investigations. The simulation results are structured according to the hierarchical control architecture to clearly demonstrate the effectiveness of each layer. The performance of each layer is validated using MATLAB/Simulink 2019b software version for before real-time implementation. Firstly, the high-level Charging Management System (CMS) is assessed platform in terms of optimal scheduling and cost minimization. Secondly, the mid-level control algorithm is also evaluated based on its ability to manage module activation and ensure balanced power sharing. Subsequently, the low-level control performance is analyzed with respect to DC-link voltage regulation and current tracking accuracy. Finally, the overall system is validated experimentally using a 45 kW prototype, highlighting the practical feasibility, scalability, and operational benefits of the proposed DC charging dispenser for large-scale urban deployment alongside conventional AC charging infrastructure.

4.1. High-Level Optimized and Scheduling Assessment

This subsection evaluates the performance of the proposed HL-CMS, which determines optimal charging schedules based on electricity pricing, EV demand, and system constraints. The objective is to minimize operational cost while ensuring that all EV charging requirements are satisfied within their respective deadlines. To validate the strategy, the timing of EV charging and discharging during a day (24 h) starting from 12:00 AM to midnight is considered the use case. The day is evenly divided into 24 intervals. Each interval has a length of 1 h and time step of 15 min. The optimized charging profile is

the output of the high-level charging management block. The EV user inputs (such as arrival time, departure time, initial SoC, battery voltage, battery nominal capacity) are the significant inputs, as shown in Table 2.

Table 2. Required EV user input to utilize the optimized charging or V2G profile.

	Arrival Time	Departure Time	Initial Energy (kWh)	Nominal Voltage (V)	Nominal Capacity (kWh)	V2G Service
EV1	2 am	2 pm	10.36	400	37	No
EV2	2 pm	2 am	4.67	400	37	No
EV3	11 am	11 pm	8.94	400	37	Yes
EV4	1 pm	12 am	8.10	400	37	No
EV5	6 pm	12 am	12.34	400	37	No
EV6	12 pm	12 am	2.57	400	37	No
EV7	8 am	8 pm	7.65	400	37	Yes
EV8	1 pm	12 am	1.07	400	37	Yes

The HL-CMS block generates an optimized power profile based on EV user input. In this section, one charging container is considered to analyze the results. There are 8 EVs booked to charge with container 1. The EV user input for EV charger 1 is listed in Table 1 below. The total load consists of the base load, which represents the load of all electricity consumption in the interval except EV charging, and the charging load, which represents the load of EV charging.

The optimizations of EV charging are based on only temporal variation, but not spatial variation in the price. The electricity price is modeled as a linear function of the instant load [8], which is shown in Figure 7, where 0.0106 €/kWh and 0.008 €/kWh/kW are considered the intercept constant (β_0) and slope (β_1) values. The charging station load profile with optimization and without optimization is shown in Figure 8.

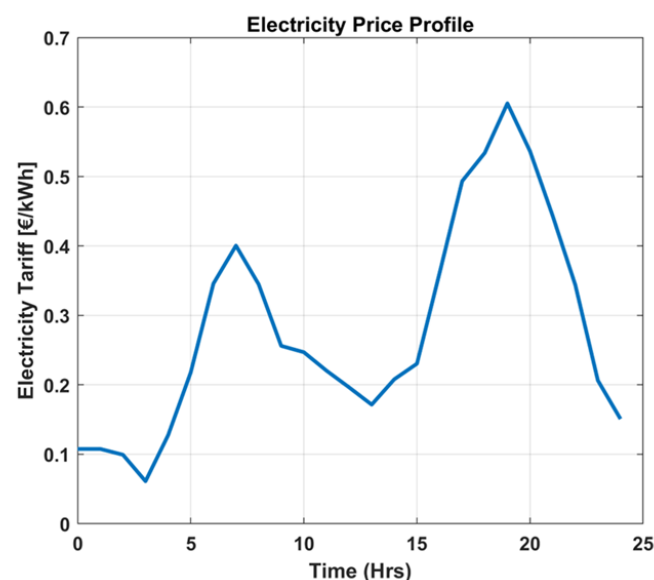


Figure 7. The electricity price profile whose variation followed the load profile pattern.

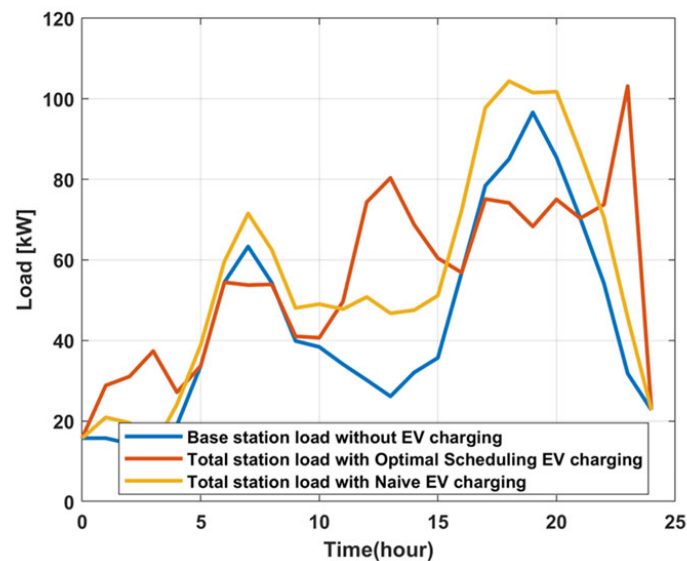


Figure 8. The impact of optimized CMS on the overall station load profile.

The “base station load without EV charging” refers to the power consumption or electrical load of a charging station when no electric vehicles (EVs) are being charged. The graph compares station load under three scenarios over 24 h: base load (blue), optimal EV charging (red), and naive EV charging (yellow). The sharp increments indicate simultaneous charging, which could not be beneficial for the infrastructure. While both EV charging methods raise the total load compared to the base case, optimal scheduling better distributes the load across the day by minimizing peaks. This makes it more efficient and grid-friendly than naive charging, which introduces volatile demand patterns. The top graph in Figure 9 shows the electricity tariff over 24 h reaching a peak around 19 h at €0.60/kWh and dropping to a low near 3 h at €0.07/kWh.

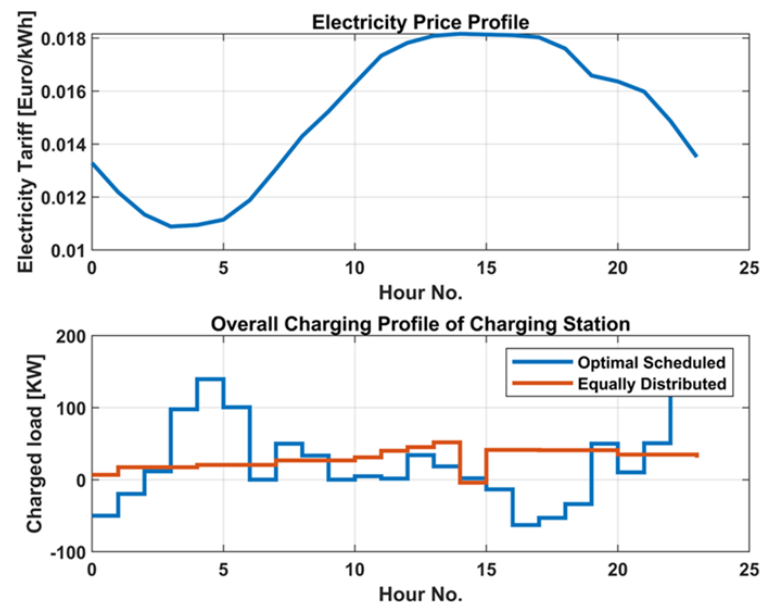


Figure 9. The scheduled optimized and non-optimized charging load profile for the overall charging station with the electricity price.

The bottom graph in Figure 9 compares the optimized charging profile with an equally distributed charging profile, which maintains a consistent load (~30–45 kW) throughout the day. In contrast, the optimized profile aligns charging with lower tariffs, concentrating

loads during off-peak hours (e.g., 1–3 h and 23–24 h) and minimizing use during expensive periods (e.g., 18–21 h). Notably, the optimal strategy even features negative loads during high-tariff hours, suggesting discharging or load shifting. This approach significantly reduces electricity costs by exploiting tariff variations. Figure 10 illustrates a comparison between optimized and unoptimized energy consumption profiles relative to fluctuating electricity tariffs over 24 h. The electricity tariff, orange, reaches a peak of €0.65/kWh at approximately 19:00, while decreasing to a minimum of €0.20/kWh during the early morning and late-night hours. The optimal energy profile, solid blue, strategically shifts power demand toward periods with lower tariffs, specifically before 07:00 and after 21:00. This is notably evident between 17:00 and 21:00, where usage peaks at nearly 75 kWh. Consequently, these two plots at Figure 10 are complementary, as they provide both instantaneous and cumulative perspectives of the scheduling performance.

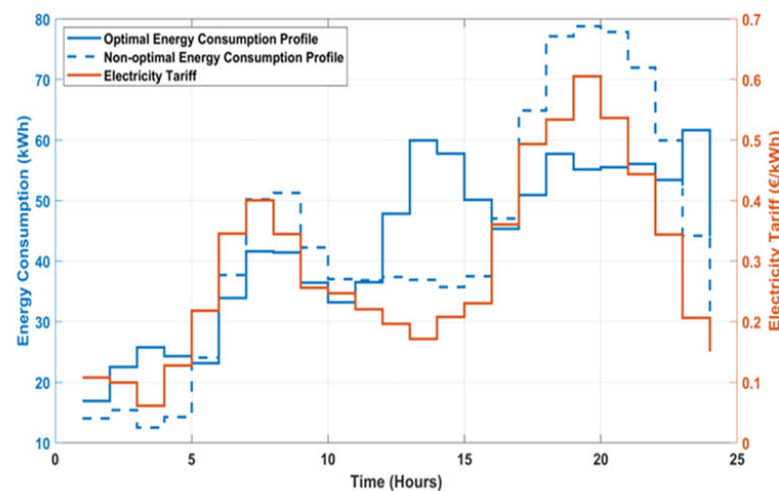


Figure 10. Energy consumption profile with optimal and non-optimal scheduling compared with the electricity price.

4.2. Mid-Level Modular Power-Sharing Assessment

This subsection presents the performance of the mid-level control layer, responsible for the hysteresis-based activation mechanism ensuring that modules are activated or deactivated only when the total current demand crosses predefined thresholds. This prevents frequent switching and improves system reliability. To assess the performance assessment of the mid-level power-sharing strategy, the following parameters, as shown in Table 3, are considered during algorithm implementation.

Table 3. Required parameters for the performance assessment of mid-level power-sharing strategy.

Parameters	Values	Parameters	Values
Rated module power P_{mod}	15 kW	Activation hysteresis ΔI_{up}	+5 A
Battery nominal voltage V_{bat}	400 V	Deactivation hysteresis ΔI_{down}	−5 A
Rated module current I_{rated}	37.5 A	Current-sharing tolerance	±5%
Number of modules	3/unit	Mid-level Control update rate	100 ms
Total system power	45 kW/unit		

Figure 11 presents the optimal charging management performance specifically for EV7. As observed in Figure 11a, the optimal scheduling strategy elevates the state of charge (SoC) of EV7 from 0% to 100% between 08:00 and 17:00. In contrast, an equally distributed strategy yields a gradual SoC increase from 20% to roughly 90% over the same timeframe, utilizing a constant charging rate of approximately 5 kW.

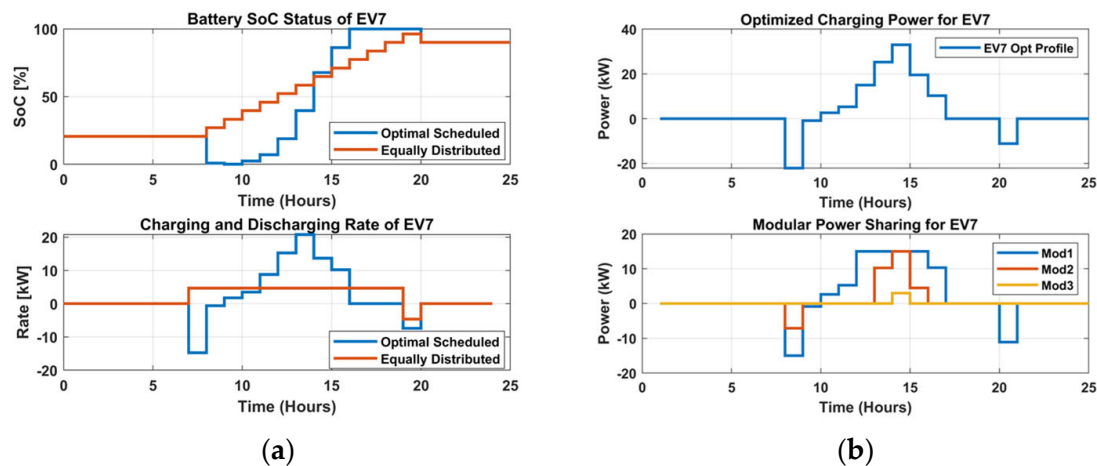


Figure 11. (a) Charging rate and SoC variation for optimized and non-optimized charging schedules. (b) Modular power-sharing performance during charging and V2G service with optimal scheduling.

The optimized schedule demonstrates a highly dynamic and efficient utilization of available power. By actively adjusting both charging and discharging rates in response to temporal parameters and grid conditions, it achieves a complete charge more rapidly. The corresponding modular power distribution, detailed in Figure 11b, indicates that Mod1 provides the largest contribution at 15 kW, followed by Mod2 at 10 kW and Mod3 at 3 kW. This coordinated modular allocation effectively sustains the optimal profile by dynamically distributing the charging and discharging loads across the three modules over the operational period.

4.3. Low-Level Voltage and Current Control Assessment

The low-level voltage and current control is implemented based on the converter designed parameters and validated the performance in MATLAB/Simulink. The selected converter specification including LCL filter is listed in Table 4 below.

Table 4. Required parameters for the performance assessment of low-level power-sharing strategy.

Parameters	Values	Parameters	Values
Rated power P_{mod}	15 kW	Selected Switching Frequency	20 kHz
Battery nominal voltage V_{bat}	400 V	Grid Side Inductance	17 μ H
Rated module current I_{rated}	37.5 A	Converter Side Inductance	3600 μ H
Rated AC Voltage, V_{grid}	380 Vrms	Filter Capacitance	33 μ F
Rated AC Supply Current, I_{grid}	23 Arms	Damping Resistance	0.25 Ω
Voltage Control Gain, kp	0.0134	Current Control Gain, kp	159.93
Voltage Control Gain, ki	6	Current Control Gain, ki	3.5690×10^6

The controller gain is selected through analyzing the frequency response for the switching frequency range 5 kHz to 30 kHz. The dynamic response of the current and voltage controller is demonstrated under step changes in charging demand.

Figure 12 demonstrates stable control performance under dynamic conditions. The d-axis current exhibits a transient peak of approximately 200 A, settling to around 30–35 A within 0.3–0.5 s. The DC-link voltage tracks the reference from 650 V to 750 V, with overshoot below 10% and settling time of approximately 0.4 s. Therefore, it is clear that the controller shows an acceptable transient response with minimal overshoot and steady-state error. Additionally, the DC-link voltage remains stable within acceptable limits during load variations.

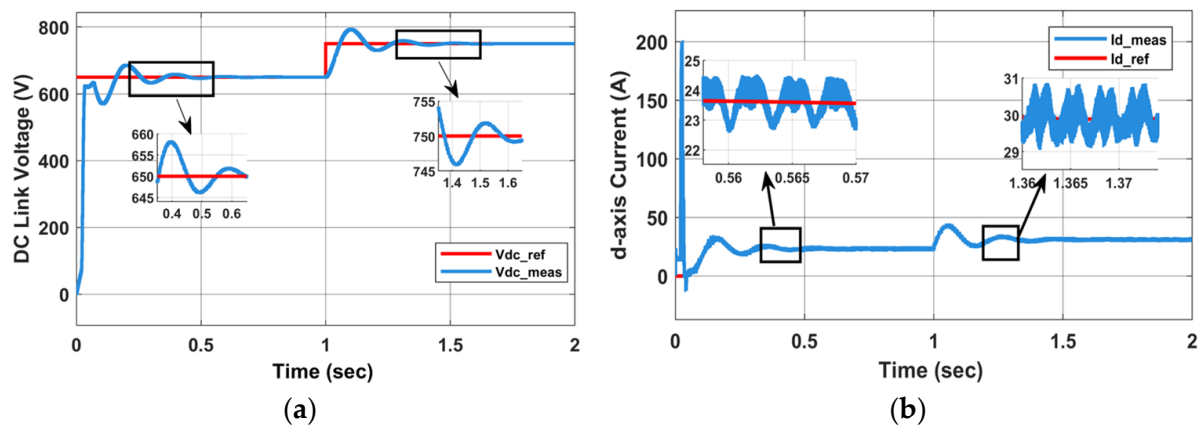


Figure 12. (a) DC-link voltage control performance assessment; (b) d-axis current control performance assessment during charging session.

4.4. Experimental Validation of Proposed Charging System

In this section, the experimental validation of the 45 kW modular and scalable DC charging station is discussed. The aim of this section is the performance assessment of the modular DC charging station hardware setup, including charging current sharing, power quality, bidirectional power flow, etc.

4.4.1. Modular Charging Container Prototype

In this experimental validation, the 45 kW rated DC charging station's internal block diagram, shown in Figure 13, is implemented with three 15 kW bidirectional isolated EV charger modules. The detailed design of the 15 kW bidirectional EV charger module is not the focus of this paper. The main contribution is a 45 kW (3×15 kW) EVSE integrated with modular PE converter. The EVSE container has three main sections. The first section consists of 3×15 kW bidirectional AC/DC converter connected in parallel, as shown in Figure 14. Each of the converters has its own low-level controller, forced air-cooling fan, CAN communication port, and necessary voltage–current protection devices. The maximum charging current will be around 65 A. Thus, an MCCB with 80 A rupturing capacity is installed by considering more than 25% safety margin. The RCD with 30 mA is also installed according to the IEC 60364-7-722:2015 safety standard [23]. This RCD device will protect the user from electric shock. The maximum DC output of the AC/DC converter is 500 V; thus, a DC PRE-charge and discharge relay with 1000 V maximum switching voltage and 400 A rated current is inserted in series.

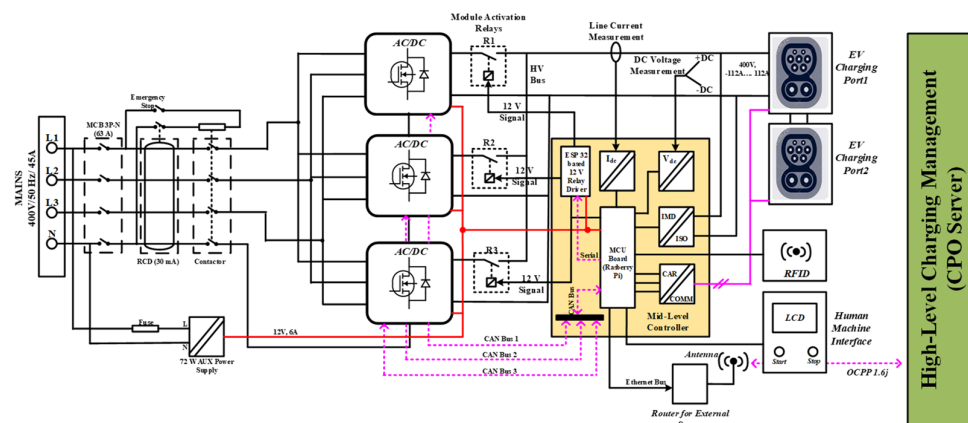


Figure 13. Internal block diagram of the 45 kW modular and scalable charger container.



Figure 14. Hardware prototype of 45 kW rated modular DC charging container.

4.4.2. Experimental Setup and Proposed EVSE Performance Validation

The block diagram of the overall experimental setup is shown in Figure 15a. The 45 kW rated EVSE is implemented with a 3×15 kW EV charger module, which has internal galvanic isolation. EVSE takes 3-ph AC power from the grid and provides the DC output to charge the EV battery.

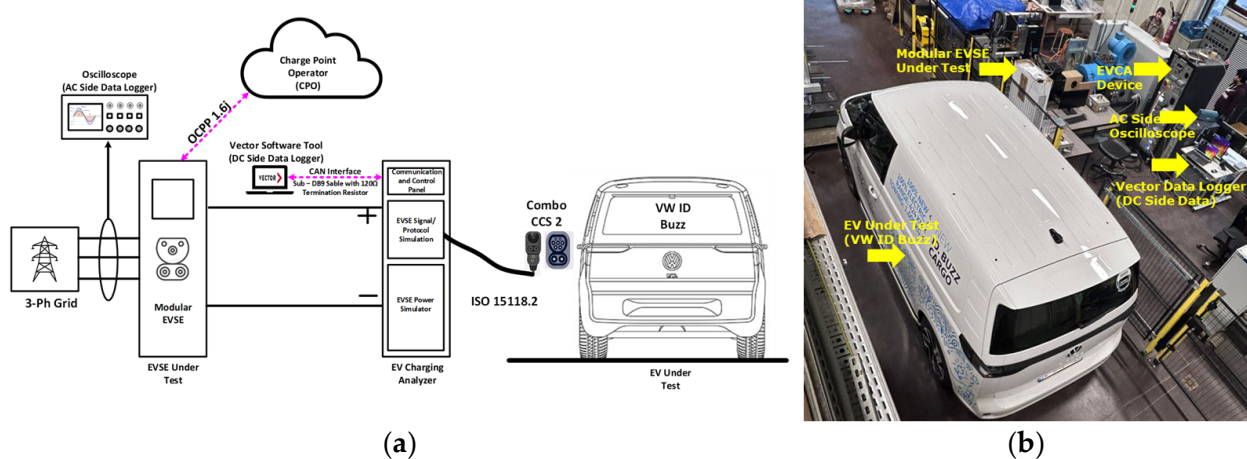


Figure 15. (a) Block diagram of experimental setup for modular and scalable DC charging station performance testing. (b) Laboratory setup for the performance test of a 45 kW modular and scalable charger container with VW ID Buzz.

The EV model is a used Volkswagen ID Buzz, which is a fully electric van. The full specifications of the EV under test are detailed in the following section. The EVSE consists of a WiFi communication module to communicate with the CPO via OCPP 1.6j protocol to start/stop the charging or V2G session based on the RFID authorization. The EVCA is installed between the DC output of the EVSE and EV battery terminals, as shown in Figure 15b. Thus, the charging power flows from EVSE to EV battery through the charging analyzer, which can control, store, analyze, and visualize the data.

The VECTOR-CANoe (release 4) software tool is used to operate the EVCA during the test. The ISO 15118.2 communication protocol is used to monitor and control the interaction between EVSE and EV through the control pilot pin [24]. The battery voltage and current performance are shown in the following. Figure 16a The operator specifies the charge and discharge current setpoints on EVCA. Initially, the charging current is set to -45 A, and then it is increased to 109 A. The battery voltage starts from around 360 V and increases during charging. The charging test is performed by varying the charging rate from 5 kW to 45 kW. At a 5 kW charging rate, the battery absorbs around 15.7 A at 360 V. Similarly,

the battery takes around 73 A and 101 A during 25 kW and 45 kW charging rates. The charging current ripple is 12 A, which is around 9.6% of the charging station's rated current. Conversely, the discharging setpoints increased from 45 A to 109 A.

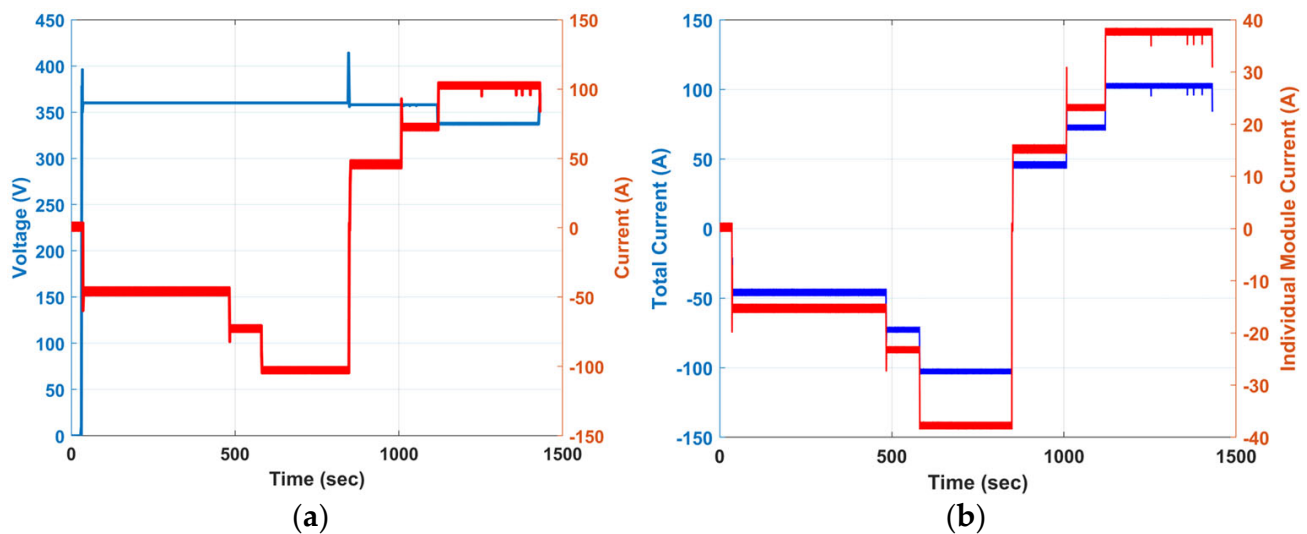


Figure 16. DC voltage and current profile during charging and V2G test. (a) Total DC voltage and current. (b) Individual module current compared to total DC current during charging and V2G.

The battery voltage decreased to 340 V during discharge. The EV battery discharging was also tested with a variable rate from 5 kW to 45 kW. The discharging current is around 45 A and 102 A at 15 kW and 35 kW discharge rates. The discharge current ripple is almost the same as the charging current ripple. The modular EVSE system allows the sharing of the charging and discharging current among 3 charging modules. The measured total and individual DC currents are depicted in Figure 16b. The AC side performance is also investigated during charging and V2G. The EVSE container demands around 37 Arms at 233 Vac (Ph) current from the during charging the battery at 25 kW, as shown in Figure 17a. Each charging module delivered 12.5 Arms at 233 Vac (Ph), as shown in Figure 17b. The THD of the charging current is 4.3%, estimated via FFT analysis using MATLAB/Simulink.

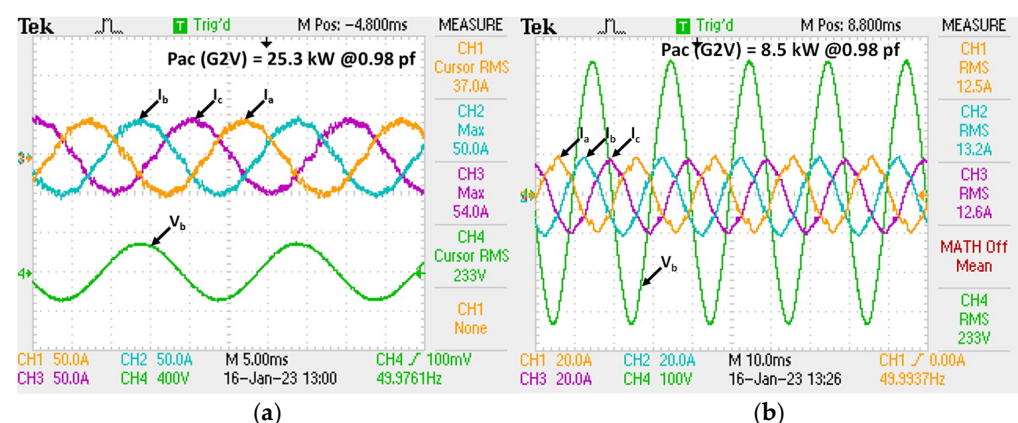


Figure 17. AC voltage and current performance during 25 kW charging test. (a) Total voltage and current waveforms. (b) Individual module AC voltage and current waveforms.

Similarly, the charger delivers 24 Arms back to the grid during 16.5 kW V2G operation, as shown in Figure 18a. The individual module delivered 8 Arms during 15 kW power transfer from the battery to the grid, as shown in Figure 18b. The THD during V2G is estimated 5.7%, which is higher than the charging operation.

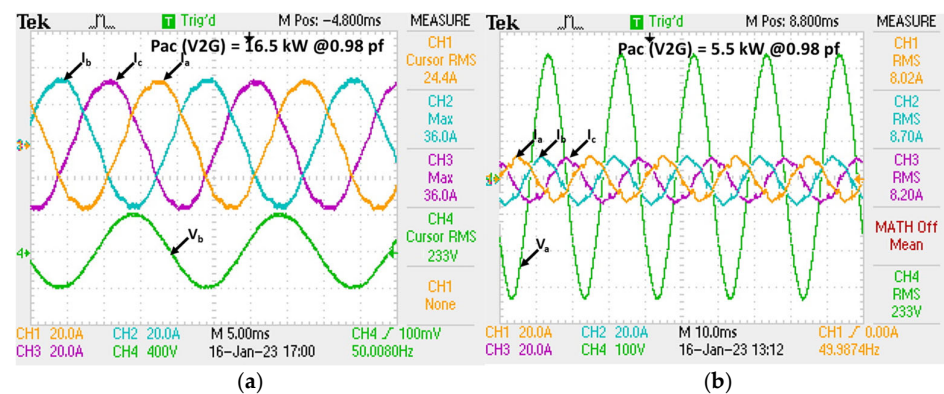


Figure 18. AC voltage and current performance during 15 kW V2G test. (a) Total voltage and current waveforms. (b) Individual module AC voltage and current waveforms.

Figure 19a presents the efficiency map of the 45 kW modular EVSE as a function of charging and discharging power. The efficiency exceeds 95.5% at high power levels ($\approx 40\text{--}45 \text{ kW}$) and decreases to approximately 92–93% near low-power operation (around 5 kW), with the minimum efficiency observed close to zero power transfer. Figure 19b compares the efficiency of a modular charger and a dedicated charger over increasing load. At rated power, the modular charger achieves approximately 96.2% efficiency, compared to 94.2% for the dedicated charger, corresponding to an improvement of about 2%, while also showing superior part-load performance.

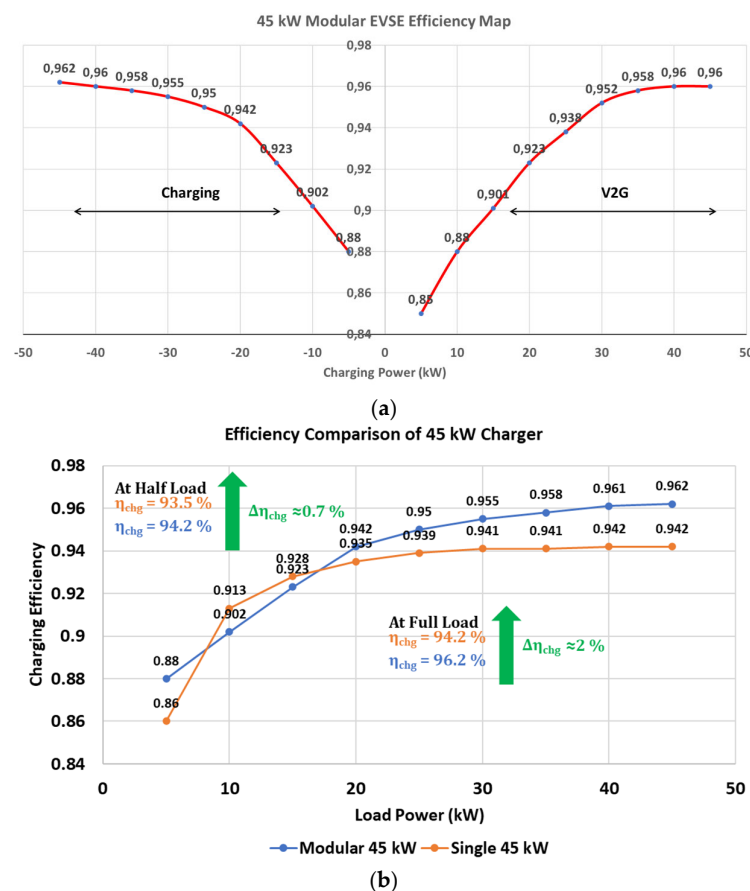


Figure 19. The measured efficiency map of modular 45 kW charger. (a) The efficiency map of 45 kW during charging and V2G. (b) The charging efficiency of modular 45 kW is compared with the measured efficiency of single 50 kW DC charger module.

The modular DC charging system provides several benefits compared to dedicated charger modules. The modular and scalable DC charging station demonstrates significant advancements in three key performance metrics. Firstly, charger efficiency for a 45 kW charging scenario improved by 2%, increasing from approximately 94% with a dedicated charger to 96% using the modular charger, as shown in Figure 20a. Secondly, in terms of charging cost, which is depicted in Figure 20b, the adoption of optimal charging reduced the overall cost by 11%, decreasing from approximately €360 with equal distribution to around €320 under the optimized strategy. Additionally, the station's peak demand experienced a substantial reduction due to the optimal charging strategy. The peak load demand decreased by 31%, as shown in Figure 20c, from nearly 110 kW to 75 kW. These results highlight the effectiveness of the modular charging architecture in enhancing operational efficiency, reducing energy expenditure, and alleviating grid stress through peak demand management. Lastly, the impact of the number of charger modules on the charging duration is illustrated in Figure 20d. The modular DC charging station reduced total charging duration from 3.8 h (1 module) to 2.4 h (10 modules), which demonstrates enhanced scalability and efficiency for simultaneous multi-vehicle charging. The average battery rated capacity is 77 kWh is considered for this assessment. Therefore, these achievements underscore the modular DC charger's potential for scalable and energy-efficient electric vehicle infrastructure.

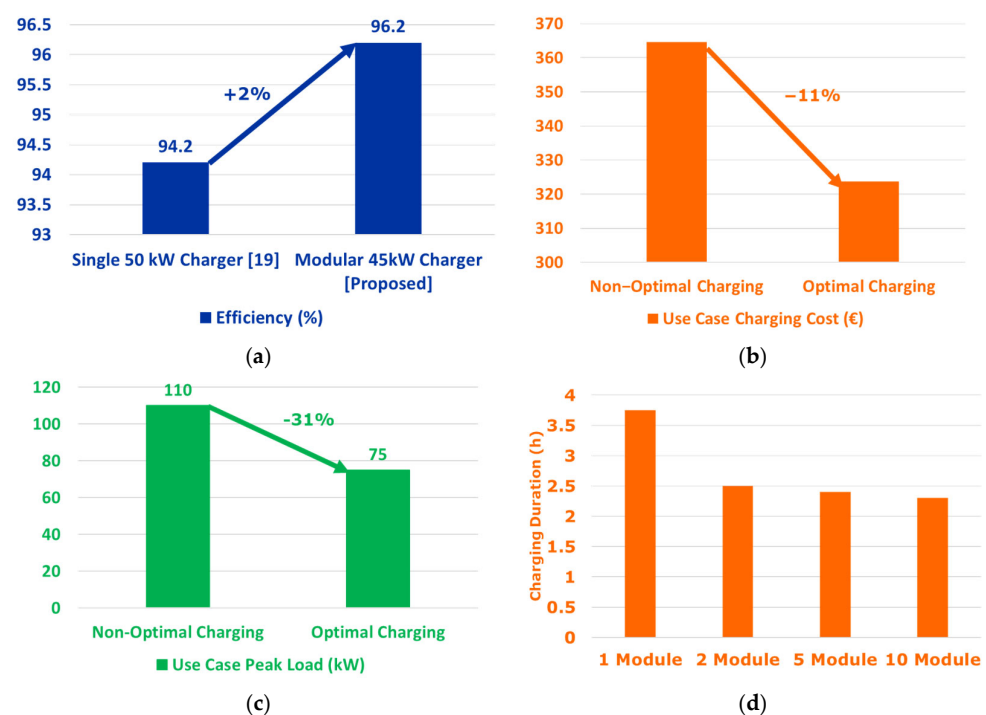


Figure 20. The operational benefits of a modular DC charging station, including optimal charging strategy (a) efficiency improvement compared to existing dedicated charger module [19], (b) overall charging cost benefit, (c) station peak demand comparison of modular charging station with optimal charging strategy, and (d) impact of the number of power modules on the charging duration.

5. Conclusions

This paper presented the implementation and validation of a distributed V2G-enabled multiport DC charging system integrated with a hierarchical charging management strategy, specifically developed for EV fleet charging hubs. The proposed architecture overcomes key limitations of centralized power converter cabinets, including single-point failure risks, high-current DC distribution losses, and limited flexibility in vehicle-level energy management by distributing bidirectional power converters within individual multiport

dispensers. The hierarchical control framework effectively coordinated charging and V2G operations across multiple time scales, ensuring stable converter operation, efficient power sharing, and grid-friendly behavior. Experimental results from a 45 kW prototype demonstrated effective power sharing among charging modules, with system efficiencies exceeding 95% during high-power operations. The modular architecture achieved an efficiency improvement of up to 2% at rated power compared to a dedicated charger, while maintaining efficiencies above 95% during high-power operation. Furthermore, the optimization-based charging management strategy resulted in an overall charging cost reduction of approximately 11% and a peak load demand reduction of up to 31%, thereby mitigating grid stress and enhancing system reliability. Bidirectional power flow, effective modular current sharing, and total harmonic distortion within regulatory limits were experimentally verified for both charging and V2G modes. Overall, the proposed distributed multiport charging system provides a scalable, resilient, and grid-supportive solution for next-generation EV fleet charging hubs and represents a viable pathway toward efficient integration of V2G services in future smart energy systems.

Author Contributions: Conceptualization, S.J., T.G. and O.H.; methodology, S.J.; software, S.J.; validation, S.J., T.G. and O.H.; formal analysis, S.J. and A.D.; investigation, S.J. and A.D.; resources, S.J.; data curation, S.J. and A.D.; writing—original draft preparation, S.J.; writing—review and editing, S.J., A.D. and M.E.-B.; visualization, S.J.; supervision, T.G., M.E.-B. and O.H.; project administration, T.G. and O.H.; funding acquisition, T.G., M.E.-B. and O.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work is an extended version of the eCharge4Drivers project (Grant Agreement 875131). This extended research activity received internal funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors also acknowledge Flanders Make for the support of our research group.

Conflicts of Interest: Authors Shahid Jaman, Amin Dalir, Thomas Geury, Mohamed El Baghdadi and Omar Hegazy were employed by the company Flanders Make (Belgium). The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
V2G	Vehicle-to-Grid
V2L	Vehicle-to-Load
EMS	Energy Management System
CMS	Charging Management Strategy
HL-CMS	High-level CMS
MCS	Megawatt Charging System
MCCB	Molded Case Circuit Breaker
RCD	Residual Current Device
RFID	Radio Frequency Identification
AC	Alternating Current
BESS	Battery Energy Storage System
SoC	State-of-Charge
THD	Total Harmonic Distortion

PLL	Phase Locked Loop
GA	Genetic Algorithm
OCPP	Open Charge Point Protocol
ISO	International Standard Organization
CAN	Controller Area Network
EVCA	Electric Vehicle Charging Analyzer
CPO	Charging Point Operator
TOU	Time of Use
DC	Direct Current
CCS	Combined Charging System

References

1. European Automobile Manufacturers' Association (ACEA). European EV Charging Infrastructure Masterplan. March 2022. Available online: <https://www.acea.auto/files/Research-Whitepaper-A-European-EV-Charging-Infrastructure-Masterplan.pdf> (accessed on 23 March 2026).
2. European Commission; Eurostat. Urban–Rural Europe—Introduction. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Urban-rural_Europe_-_introduction (accessed on 23 March 2026).
3. McKinsey & Company. Why the Automotive Future Is Electric. 7 September 2021. Available online: <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/why-the-automotive-future-is-electric> (accessed on 23 March 2026).
4. UK Government, Department for Transport. Electric Vehicle Smart Charging Action Plan. 2023. Available online: <https://assets.publishing.service.gov.uk/media/655dfabf046ed400148b9e0a/electric-vehicle-ev-smart-charging-action-plan.pdf> (accessed on 23 March 2026).
5. Ali, Z.H.; Raisz, D. Power Flow and Voltage Control Strategies in Hybrid AC/DC Microgrids for EV Charging and Renewable Integration. *World Electr. Veh. J.* **2025**, *16*, 104. [\[CrossRef\]](#)
6. Rehman, A.U.; Khalid, H.M.; Muyeen, S.M. Grid-Integrated Solutions for Sustainable EV Charging: A Comparative Study of Renewable Energy and Battery Storage Systems. *Front. Energy Res.* **2024**, *12*, 1403883. [\[CrossRef\]](#)
7. Rituraj, G.; Mouli, G.R.C.; Bauer, P. A Comprehensive Review on Off-Grid and Hybrid Charging Systems for Electric Vehicles. *IEEE Open J. Ind. Electron. Soc.* **2023**, *3*, 203–222. [\[CrossRef\]](#)
8. Abdelwanis, M.I.; Elmezain, M.I. A Comprehensive Review of Hybrid AC/DC Networks: Insights into System Planning, Energy Management, Control, and Protection. *Neural Comput. Appl.* **2024**, *36*, 17961–17977. [\[CrossRef\]](#)
9. Mamidala, S.; Prajapati, A.K. Grid-Integrated EV Charging Infrastructure. In *Recent Advances in Power Electronics and Drives (EPREC 2023)*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 297–323.
10. Tayri, A.; Ma, X. Grid Impacts of Electric Vehicle Charging: A Review of Challenges and Mitigation Strategies. *Energies* **2025**, *18*, 3807. [\[CrossRef\]](#)
11. Iranpour, M.; Narimani, M.R.; Jia, X. Assessing EV Charging Impacts on Power Distribution Systems: A Unified Co-Simulation Framework. *arXiv* **2025**, arXiv:2505.21773. [\[CrossRef\]](#)
12. Rancilio, G.; Bovera, F.; Delfanti, M. Slow but Steady: Assessing the Benefits of Slow Public EV Charging Infrastructure in Metropolitan Areas. *World Electr. Veh. J.* **2025**, *16*, 148. [\[CrossRef\]](#)
13. Raffoul, E.; Li, X. Assessing the Impact of Electric Vehicle Charging on Residential Distribution Grids. *arXiv* **2024**. [\[CrossRef\]](#)
14. Anggraini, D.; Amelin, M.; Söder, L. Electric Vehicle Charging Considering Grid Limitation in Residential Areas. In *2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA*; IEEE: New York, NY, USA, 2024; pp. 1–6. [\[CrossRef\]](#)
15. Masaya, I.; Hiroaki, M.; Kimihisa, F.; Kazuki, G.; Rei, G. Multi-Port EV Charger Contributes to Effective Energy Use 420. Solutions in an EV Society. Hitachi Hyoron. 15 June 2024. Available online: <https://www.hitachihyoron.com/rev/papers/2024/06/01/index.html> (accessed on 12 February 2026).
16. Assadi, S.A.; Gong, Z.; Coelho, N.; Zaman, M.S.; Trescases, O. Modular Multiport Electric-Vehicle DC Fast-Charge Station Assisted by a Dynamically Reconfigurable Stationary Battery. *IEEE Trans. Power Electron.* **2023**, *38*, 6212–6223. [\[CrossRef\]](#)
17. Elkeiy, M.A.; Abdelaziz, Y.N.; Hamad, M.S.; Abdel-Khalik, A.S.; Abdelrahman, M. Multiport DC-DC Converter with Differential Power Processing for Fast EV Charging Stations. *Sustainability* **2023**, *15*, 3026. [\[CrossRef\]](#)
18. Monteiro, V.; Oliveira, C.F.; Afonso, J.L. Experimental Validation of a Bidirectional Multilevel dc–dc Power Converter for Electric Vehicle Battery Charging Operating under Normal and Fault Conditions. *Electronics* **2023**, *12*, 851. [\[CrossRef\]](#)
19. Verbrugge, B.; Rauf, A.M.; Rasool, H.; Abdel-Monem, M.; Geury, T.; El Baghdadi, M.; Hegazy, O. Real-Time Charging Scheduling and Optimization of Electric Buses in a Depot. *Energies* **2022**, *15*, 5023. [\[CrossRef\]](#)
20. Ramanathan, G.; Bharatiraja, C.; Kotb, H.; Emara, A. PV-assisted modified Z-source inverter for multiport EV charging infrastructure. *Energy Rep.* **2024**, *11*, 5716–5732. [\[CrossRef\]](#)

21. Zhaksylyk, A.; Rasool, H.; Geury, T.; El Baghdadi, M.; Hegazy, O. Masterless Control of Parallel Modular Active front-end (AFE) Systems for Vehicles and Stationary Applications. In *2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte-Carlo, Monaco; IEEE: New York, NY, USA, 2020; pp. 1–6. [[CrossRef](#)]
22. Jaman, S.; Abdel-Monem, M.; Geury, T.; Hegazy, O. Development and Validation of an Integrated EV Charging Station with Grid Interfacing Inverter for Residential Application. *IEEE Access* **2023**, *11*, 115751–115774. [[CrossRef](#)]
23. IEC 60364-7-722:2015; Low-Voltage Electrical Installations—Part 7-722: Requirements for Special Installations or Locations—Supplies for Electric Vehicles. International Electrotechnical Commission: Geneva, Switzerland, 2015. Available online: https://cdn.standards.iteh.ai/samples/18235/db81b17e3a9947168fc4cec2ec54f900/IEC-60364-7-722-2015.pdf?utm_source=copilot.com (accessed on 5 April 2026).
24. ISO 15118-2:2014; Road Vehicles—Vehicle-to-Grid Communication Interface—Part 2: Network and Application Protocol Requirements. International Organization for Standardization: Geneva, Switzerland, 2014. Available online: https://www.iso.org/standard/55366.html?utm_source=copilot.com (accessed on 5 April 2026).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.