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EV Smart-Charging Strategy for Power Management in Distribution Grid with High Penetration of Distributed Generation

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Abstract: Accelerated environmental impacts are a growing concern in the modern world. Electric mobility and the transition to a cleaner energy matrix have become increasingly discussed topics. In this context, this work presents a framework for controlling an electric vehicle (EV)-charging station integrated into a microgrid application as a basis for creating the infrastructure integrated into a smart grid concept. Considering the electrification of the transportation sector future perspectives, a brief review is conducted on the impacts of EV fleet growth in different countries and how smart-charging technologies are identified as solutions for mitigating the negative effects of energy and power consumption associated with EV-charging stations. An analysis of the technical characteristics and the tools that enable the deployment of a fleet-charging operator are examined, specifically focusing on the communication protocol for EVs, such as the OCPP (Open Charge Point Protocol) parameterization/configuration. A new EV-charging station control method is proposed to manage the impacts of distributed solar photovoltaic generation and mitigate the effects of the duck curve. Finally, an integration architecture via IEC 61850 for these elements is proposed, in a practical implementation for variable power control, considering different strategies to deal with distributed generation impact using EV-fleet-charging power demand dynamic management.

Keywords: OCPP; IEC 61850; electric vehicles; microgrid; charging stations

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Citation: Maia, G.L., Jr.; Santos, C.C.L.; Nunes, P.R.M.; Castro, J.F.C.; Marques, D.C.; Medeiros, L.H.A.D.; Limongi, L.R.; Brito, M.E.C.; Dantas, N.K.L.; Filho, A.V.M.L.; et al. EV Smart-Charging Strategy for Power Management in Distribution Grid with High Penetration of Distributed Generation. *Energies* **2024**, *17*, 5394. https://doi.org/10.3390/en17215394

Academic Editor: Islam Safak Bayram

Received: 2 October 2024
Revised: 22 October 2024
Accepted: 23 October 2024
Published: 30 October 2024

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1. Introduction

Climate change and health issues in large urban centers, stemming from greenhouse gas emissions, are among the greatest sustainable development challenges faced by modern society [1–4]. Due to the growing struggles against the advancement of these factors, there is significant concern about achieving the goals of mitigating environmental damage, air quality, and public health through the reduction in the emissions [5,6].

In 2014, approximately 14% of global CO_2 emissions originated from the transportation sector [7]. From the perspective of emission sources, in the USA, a report by the Environmental Protection Agency (EPA) found that in 2019, about 28% of the country's greenhouse gas emissions came from transportation, primarily from the combustion of fuel in internal combustion engine vehicles [8].

One of the main solutions proposed globally for reducing pollutant gas emissions is electric mobility, considered an emerging strategic industry [1–3,5,6]. Electric mobility is identified as a key factor in achieving carbon neutrality in Europe by 2050 [6]. Various entities, including countries, provinces, governmental institutions, and vehicle manufacturers,

emphasize the urgency of this matter by committing to cease the production or acquisition of new internal combustion engine vehicles at different points over the next 40 years [5,9].

Consequently, it is also necessary to consider that the electrification of transportation may present new challenges. The growth of the electric vehicle (EV) fleet will affect not only the spatiotemporal distribution of pollutant emissions [5] but also the energy distribution profile in major urban centers. The supply of electrical power for recharging is geographically linked to the route and permanence of the vehicle. Therefore, the feasibility of recharging is also conditioned by the availability of capacity in the power transmission grid [10].

The interoperability of devices and communication between different agents in the power grid are essential for the development of smart grids [11]. For example, to control an EVSE (Electric Vehicle Supply Equipment), a well-established communication structure is necessary. The interaction dynamics between the equipment occur at the software level through communication protocols, which are, in summary, a set of definitions for the structure of the data exchanged between two or more devices. Communication protocols establish the rules for correctly receiving and sending data and information [12].

The IEC 61850 standard [13] is an international standard for the automation of energy distribution and the control of electrical substations, as well as for the control of distributed energy resources [14]. Due to its structure that applies the object-oriented programming paradigm [11,14–16], it has a very broad range of applications. Ideally, any type of communication object can be implemented, and consequently, it is possible to communicate with a wide range of devices with diverse functions and from different manufacturers [11]. Thus, the protocol established by the IEC 61850 standard is presented as a tool with high potential for use by a fleet operator to integrate the agents of a smart grid [11,14,15].

The OCPP—Open Charge Point Protocol—is the communication protocol currently accepted by the EVSE industry for communication between the charging station and its control system, such as the FO (Fleet Operator) or some other type of intelligent system [11,17]. When integrated with IEC 61850, it allows the FO to treat the EVSE as a distributed resource unit in the network. Therefore, considering the established communication standards, the objective is to propose a framework for the relationship between the FO and the EVSE through the OCPP communication protocol. To this end, a necessary requirement is to identify how the protocol establishes and maintains communication, what type of information the EVSE can exchange with the FO, and how communication with electrical sector equipment (for example, via IEC 61850) can be structured.

1.1. Electric Fleet Growth and Grid Impacts

It is common for studies to consider different scenarios of EV market penetration [18], that is, a comparison between the current share of demand and the potential share of demand. The higher the penetration rate, the greater the spread of the technology [19]. These scenarios include, for instance, general market conditions, shocks in gasoline supply, changes in vehicle prices, government subsidies, tax exemptions, among others [18].

In 2012, Al-Alawi and Bradley [18], in their literature review on EV market forecasting studies, presented some of the barriers or factors impacting a buyer's predisposition to opt for EVs: lack of familiarity with the technology, battery lifespan, battery replacement cost, fuel cost, uncertainties about vehicle range, uncertainties about cost–benefit, different purchasing options, social and digital influence, and vehicle class. Given these factors, their analysis results indicated that by 2020, in the U.S., with an active policy of promoting PHEV technology, it would be possible to achieve around 4% to 5% of the total vehicle sales share and have 2% to 4% of market penetration. According to data from the Statista data collection and analysis platform [20,21], in 2019, approximately 4.72 million vehicles were sold in the U.S., of which about 0.32 million were EVs, including BEVs (Battery Electric Vehicles) and PHEVs (Plug-in Hybrid Electric Vehicles), totaling about 6.7% of the total, surpassing initial forecasts.

In more recent literature, Kapustin [3] used a logistic growth methodology to forecast the impact of EV fleet growth on the electric grid. This methodology predicts the growth of product units in the market through an S-curve approximation, with growth accelerating at the beginning of the product's spread and decelerating from the middle to the end as the market nears saturation. According to the analysis, by 2040, the number of EVs will have grown by 60 to 70 times, reaching about 12% to 28% of the global fleet, depending on the scenario.

Shepherd [22] proposes a market diffusion model that considers buyer susceptibility based on different premises, such as subsidy regimes, marketing strategies, BEV characteristics, EV lifespan, taxation, and information diffusion through interpersonal relationships. Among three different scenarios in the model, it is predicted that by 2050 in the United Kingdom, the BEV and PHEV fleet could account for 36.5% to 47.43% of the total fleet.

Ref. [23], also analyzing the impact on the electric grid and using the same forecasting method as Kapustin [3], predicted that, from 2020 to 2030, the EV fleet in the city of Campinas-SP, Brazil, could increase by 76 to 168 times, from 392 vehicles in 2020 to 29,000 to 66,000 in 2030. In recent years, EVs have been considered the conventional solution for pollutant gas emissions. However, due to the accelerated and hard-to-predict disruptive growth of electrification [24], both positive and negative consequences may arise.

Different impact management strategies have been adopted, considering energy aspects. Solar photovoltaic generation can be locally integrated with EV-charging stations to reduce grid consumption [25]. Microgrids are a natural strategy for power coordination in variable loads, despite the challenges related to regulatory and technical requirements for connection to distribution systems [26]. To mitigate electrical impacts associated with peak power, battery storage systems can be employed [25,27]. However, the use of storage systems can reduce financial attractiveness and compromise economic viability [28]. Therefore, a strategy could be load management through power control techniques for charging stations, with the integration of communication systems (IEC 61850 and OCPP, for instance), forming an intelligent grid with coordinated management.

Green, in [29], conducted an extensive and important literature review of 25 different sources on the impact that an EV fleet can have on the power grid. The review highlights the importance of this type of study, and by comparing different forecasting and impact models, we can increasingly approach models that resemble real scenarios, enabling and promoting increasingly accurate and reliable results. The study points out various factors and characteristics of vehicles, consumers, and the electrical grid itself, each having impacts on energy balance and infrastructure in their own way.

Generally, [29] noted that there are different perspectives on this issue. For example, evaluating the impact on a macro level, considering the global variation in energy consumption, shows whether infrastructure expansion is necessary. The literature reviewed by Green indicates that although the global impact of predicted consumption is small percentage-wise, this consumption will evidently be geographically imbalanced, with higher concentration in large urban centers. From this point, other studies reviewed by Green assess local impacts, now considering micro factors, such as:

Charging Profile—The considerations of profile among studies vary. The profile can be generic, "anytime during the day", referred to as uncontrolled or uniform charging; it can revolve around user behavioral patterns, for example, at the beginning of the day when the user arrives at the destination, such as the workplace, or at the end of the day when the user returns home after completing their daily commute; it can be related to the presence of fast and slow charging in the mix of chargers; it can be related to the level of information and communication between charging points, referred to as Regulated Charging, when there is some level of information dissemination affecting user preference for charging during off-peak times, and Unregulated Charging otherwise; or still, considered the most advanced type of charging, Smart Charging pertains to all types of charging that implement intelligent decision-making technologies.

Consumption Profile and Renewable Energy Matrix—There is an interaction between the population's energy consumption profile, the charging profile, and the presence of renewable sources like solar and wind energy in the energy matrix. With extensive renewable generation infrastructure, intelligent load management is necessary due to the irregular energy availability throughout the day. Ideally, the literature suggests that energy storage systems should store surplus energy during generation peaks and provide it during low-generation periods. Additionally, EVs should ideally be charged during generation peaks to avoid load during low-generation times.

Local Transformer Capacity—It is observed that electrical grid transformers tend to have a reduced lifespan related to how close they operate to their limits, as well as large load variations during operation. Some studies indicate that depending on the charging scenario and the speed of fleet electrification, transformers may have their lifespan shortened by operating marginally at their limits. Additionally, they may have a higher probability of failure due to oscillations or might not support the load, requiring infrastructure investment.

In [3], Kapustin used a complex modeling tool, SCANER, which consists of a sophisticated system composed of different forecasting tools. The study predicts that by 2040, global energy consumption could be 7% to 10% higher compared to the scenario without EVs, with the increase geographically concentrated in regions already showing growing EV penetration, such as the USA, China, and the European Union. In some cases, the study predicts that energy consumption from EVs could reach one-third of the total in a country. It is also important to note that regions with high EV penetration may present a potential issue related to a "peak-to-peak" effect on the grid, which involves a high variation between maximum and minimum energy consumption values throughout the day, potentially causing grid instabilities, necessitating case-by-case impact analysis.

Kapustin also points out that these high-penetration regions focus on planning the expansion of the renewable energy matrix, highlighting again the potential risks associated with consumption, charging, and generation profiles of these renewable sources, making intelligent management of charging profiles and energy storage necessary.

Hudson [30], studying residential circuits, used simulations with 24 different scenarios, varying parameters such as consumption profile, charging profile, residential solar generation, and residential energy storage with battery sets. The study was based on a set of 180 transformers divided among 50 kVA, 75 kVA, and 100 kVA, feeding 1422 residences distributed among them.

In the study results, Hudson observed that a comparison in the scenario without solar generation or batteries, merely changing the charging profile from uncontrolled to smart charging, could reduce peak demand by almost 100% per residence during the day, redistributing consumption between 5 PM and 11 PM to other times.

Moreover, an important addition to this study concerns analyses related to a parameter called the Equivalent Aging Factor related to transformers. The calculations showed that scenarios with significant variations in power or even the direction of power in transformers increase this factor by an average of 23% to 55%, but in specific circuits, it can increase by up to 150%, implying that, in some scenarios, the infrastructure impacts can become highly relevant. Conversely, in scenarios where smart charging was implemented, this average value could be reduced by 5% to 21% and the maximum by 7% to 45%.

As described in [31,32], despite the potential benefits, smart-charging strategies have impacts on power factor and harmonics, since EVs consume a relatively large amount of reactive power at lower currents and some models violate the power factor limits for the low-voltage grid. One of the strategies to mitigate the occurrence of electrical impacts could be the use of battery energy storage systems or the use of tools that can support the assessment of electrical impacts associated with charging for distribution network operators with low short-circuit power [33].

In summary, some of the literature supports the necessity of having an intelligent charging system. Therefore, the objective of this work will emphasize smart charging

and the supervision of EV stations, justifying the need to control EVSEs and the types of technologies involved in this process.

1.2. EV Charging Power Management Strategies and Distributed Generation Coupling

In recent years, distribution networks have been subjected to the variability of renewable sources. The penetration level of DG units, especially generation based on uncontrolled energy resources, such as PV solar, is a factor that should be controlled and may be considered as a fundamental challenge for reliable operation of EPS [34], raising concerns about grid access requisites and regulations improvement across the world [35]. The main point is that DG units depend on natural resources which are uncontrollable by humans and may create an imbalance in the supply and demand of energy in the grid known as the "duck curve". As described in [34], the duck curve, reproduced in Figure 1, derives its name based on a chart published by the California Independent System Operator (CAISO) in 2013 resembling a duck and highlights the sharp midday drop in power demand resulting from peak solar energy production followed by a short, steep ramp-up in the early evening hours as the demand for energy increases and solar energy production falls [36,37]. The graphic in Figure 1 shows the effect of growing levels of solar generation on the daily net load in CAISO's service territory [38]. Currently, the solution of this problem can be found in the application of different energy storage technologies: the energy storage system (ESS), battery energy storage systems (BESS) [24,39], fast response thermal units, plug-in electric vehicles, concentrated solar power and pumped storage hydroelectricity [40–43], or flexible generation [44,45], as well as an application of different management methods, such as demand response and demand dispatch, can be used [36,46,47]. In this paper, a strategy for dealing with the consequences of the curve is proposed based on full integration of EV-charging stations using OCPP and IEC 61850 for load management via current control during charging events.

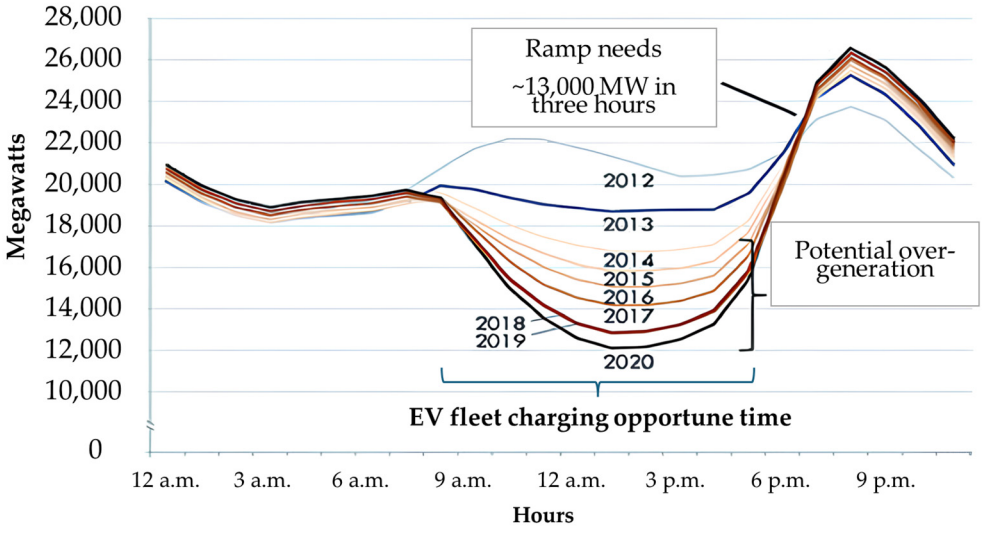


Figure 1. The duck curve—DG insertion on distribution feeders—adapted from [38].

One of the challenges associated with the duck curve format in systems with high penetration of DG is the difficulty in separating the power component of electrical loads from the power component associated with generators, as the utility meters are usually concentrated only at specific points on the feeder branches, collecting net power injection measurements. Thus, in the duck curve, the effects of load variation throughout the day are combined with the variability of distributed photovoltaic solar generation, resulting in power reduction ramps in the early hours of the day and power increase ramps at the end of the day, as illustrated in Figure 1. By managing the EV-charging stations loads connected

at the end of the feeders, as a demand-side management strategy, electrical vehicles could contribute to reduce grid impacts of distributed generation in power systems.

2. Power Grid Infrastructure Management

The use of smart-charging technology is identified as a solution for mitigating the negative effects of energy consumption, balancing the power grid, reducing infrastructure wear and tear [29,30,48], and as a factor for increasing the penetration of renewable energy systems [30]. It becomes evident that to achieve an optimal scenario, administrative intervention in the charging infrastructure is necessary, by acting on controlling and supervising the interchanges between the EV fleet and the infrastructure, especially when the Vehicle-to-Grid (V2G) energy flow technology is present. To utilize the V2G capability, it is necessary for the EV and the charging station to have the capacity for DC–AC current converter in the vehicle to grid direction [4]. Additionally, there is a need for charging stations to have access to information and be able to receive commands from a central control system, the Central System (CS), in a dynamic called the smart grid. Through smart-charging techniques, depending on the level of control between the smart grid and the charging station, the CS could provide and receive information about the current grid conditions, or even, in scenarios with a higher level of control, make charging/discharging decisions for the vehicles [49].

There are also two important potentials for using V2G, both related to a possible passive income associated with the EV market, which becomes significant when a single person or company owns many EVs. This is possible because with efficient management, it is possible to use the potential of EV batteries to be considered a distributed storage system, generating cost reductions or profit associated with the EV fleet [2,49]. These two potentials are as follows: (i) the capability to serve as an ancillary service for regulating the power grid [10]; and (ii) the ability to absorb excess generation from renewable sources such as solar and wind energy [49].

There are few studies on the management of EV charger infrastructure, Hu et al. [49], for instance, introduces the concept of an electric grid operator entity participating in the smart grid, referred to as an "EV fleet operator" (EV FO). Other names have been proposed, such as "virtual EV power plant", "EV aggregator", and "EV service provider". The study points out that an EV FO would essentially have three functions: (i) ensuring the needs of EV owners through management that maintains user parameters (e.g., always keeping the EV battery above 80%); (ii) managing the process of providing energy to the power grid during peak hours, offering greater energy balance; and (iii) providing ancillary services to various elements and operators of power systems. Figure 2 illustrates a possible scenario of integration between these different entities in the energy sector and the types of interactions the FO [49].

The ancillary services that can be provided to Transmission System Operators (TSOs) are primarily associated with power regulation, which involves increasing or decreasing the operating power of a specific system element to align it with others, but also includes frequency regulation. The use of EVs for this purpose presents substantial financial returns to owners [2]. For Distribution System Operators (DSOs), the study indicates that EV FOs can currently provide two types of ancillary services: (1) peak load prevention and loss reduction; (2) voltage regulation.

As for ancillary services to Renewable Energy Sources (RES), they are based on the increasing adoption of renewable energy generation sources, which tend to exhibit intermittent behavior, such as solar and wind energy [49]. Integration with a system capable of absorbing surplus energy during peak generation and making it available again during low generation periods presents significant utilization potential, as demonstrated by Dallinger and Wietschel [50], who showed that by 2030, in Germany, the projected EV fleet associated with the renewable energy matrix could absorb about 50% of the annual surplus generation, energy that would be lost (curtailment effect) in the absence of energy storage systems.

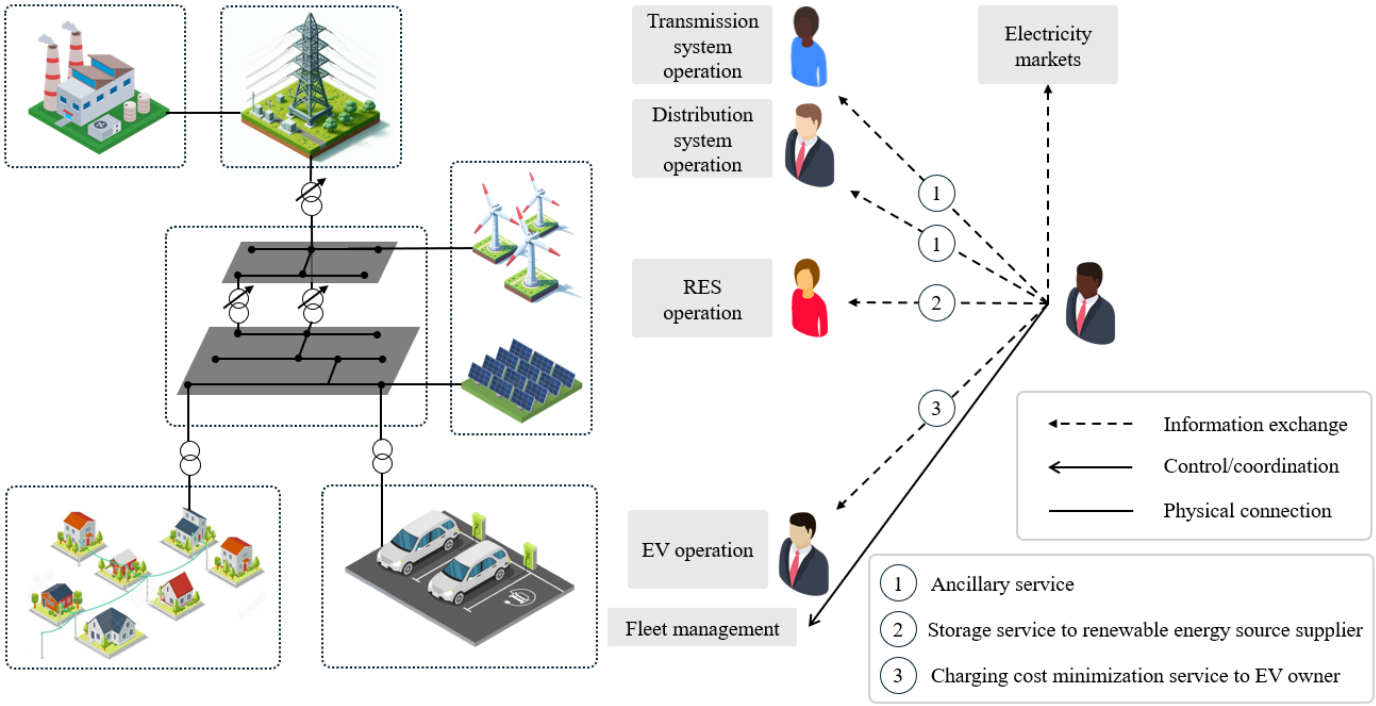


Figure 2. Relationships between the EV FO and various entities present in a smart grid—adapted from [49].

Finally, the cost-minimization services that can be provided to users through the actions of FOs need to be carefully analyzed. Dynamically programmed charging schedules applied individually to charging stations can be used to implement charging and discharging calendars for EVs depending on the value of electricity at certain times of the day. Some potentially negative points to observe in this regard are as follows: (1) additional investment costs in infrastructure enabling bidirectional energy flow; (2) deployment of advanced communication and metering systems; (3) increased battery degradation due to significantly higher usage cycles compared to scenarios without V2G [49].

3. Control and Supervision of Electric Vehicle Supply Units

An important aspect of the management offered by FOs concerns the communication infrastructure to be used. Communication between the EVSE and the EV follows an international standardization (based on ISO 15118 [51]) and does not require human intervention. On the other hand, communication between the FO and the TSO, DSO, and RES could be carried out via conventional internet, with well-established protocols and communication frameworks [12]; however, with the increasing expansion of the EV architecture, protocols specifically designed to facilitate the data interchange between its different agents may be more attractive; examples of such protocols are (1) the Open Charge Point Protocol (OCPP) used for communication between FO and EVSE, the most used for this purpose worldwide; (2) Hubject's Open Charge Protocol (OICP), widely used on Europe for communication between FO and the other external agents; (3) IEC 61850, which has the capability of standardizing the communication between all the elements; and (4) SAEJ2836/3TM, which also allows communication between distributed energy resources or EVSEs with their respective managers. The latter has the key characteristic of allowing for the V2G dynamic, because its EVSE-to-EV communication is based on IEC/TR 61850-90-7 [52]. A visual representation of the architecture showing the protocols that may be used in information transactions is illustrated in Figure 3, and information regarding the elements using the protocols is shown in Table 1 [49].

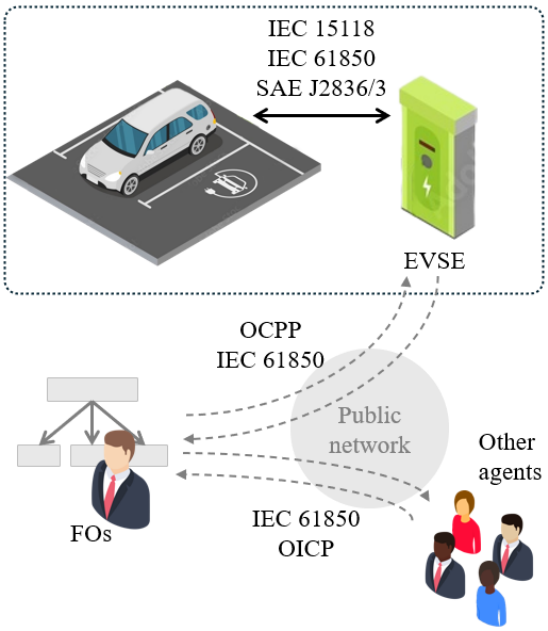


Figure 3. Communication standards of the EVSE in the context of smart grids.

Table 1. Communication standards of the EVSE in the context of smart grids.

Protocol	Elements Involved
ISO 15118	EV, EVSE
SAE J 2836	EV, EVSE
OCPP	EVSE, FO
OICP	FO, Other agents
IEC61850	All elements

Considering the potential impacts of fleet growth in the distribution power grid, in a scenario of high EV penetration, the integration between distributed charging points becomes necessary. In this regard, it is essential to understand the characteristics of the elements involved, such as charging stations specifications, and the types of connection plugs used. In 2010, a non-profit organization, ElaadNL, aimed to install 10,000 charging stations in the Netherlands and, for this purpose, began developing a protocol to standardize the control of these stations: OCPP. In 2010, the first version, OCPP 1.0, was released, which was made available from the outset as a tool to encourage the growth of the industry and the protocol itself. In 2012, with the growth of technology and the emergence of new demands, the first update, OCPP 1.5, was released [53].

In 2014, the Open Charge Alliance (OCA) was established as a non-profit organization under Dutch law. The OCA emerged from a joint effort of product and service providers, with the aim of fostering initiatives related to infrastructure systems, logistics, and research and development related to EVs. It is the institution responsible for the development and maintenance of the OCPP [53]. In 2015, OCPP 1.6 was launched, which added several new features, such as load management and the implementation of smart charging. Version 1.6 is currently the most widely used in the world. In 2018 and 2020, versions 2.0 and 2.0.1 were released, respectively. Although they were developed with a joint effort of research and industry feedback, they incorporated communication models incompatible with previous versions, which hindered their adoption [53].

For a detailed analysis of the OCPP 1.6 protocol, the official protocol documentation [17] provided by the OCA will be used as a basis, and the most relevant informative points will be explored. As it is the most globally used version and already allows functionalities such as load control and smart charging, the OCPP 1.6 protocol was chosen as the object of study. In order to standardize the nomenclature of the elements, two basic

definitions must be established: (i) the term Central System (CS) is used in OCPP to denote the equipment connected to the EVSE and exchanging information with it, and (ii) the term Charge Point refers to the EVSE itself in the protocol [17].

It is important to note that OCPP 1.6 allows the use of the WebSocket protocol for communication, enabling the implementation of usage modes based on JSON (Java Script Object Notation) or SOAP (Simple Object Access Protocol) [17]. Although the modes have their particularities, they are analogous in objectives and use similar logic. Between the two, the JSON mode was chosen for its simplicity and compatibility with the other tools that will be used in the framework proposed later in this work.

4. Proposed Control Architecture

As described previously, in order to mitigate negative fossil fuel impacts on the environment, several countries, in addition to setting ambitious renewable energy targets, are moving towards the replacement of vehicle fleets with EVs in the coming decades. The transition towards decarbonization presents individual challenges, such as the potential for transformer overloads during peak EV consumption times or surplus energy during peak renewable energy generation periods, but the integration between those technologies also offers some solutions for the problems caused by each one individually.

As previously mentioned, studies revised by Green [29] from pre-2010, had already shown that the impacts caused by the electrification of the vehicle fleets could not be dismissed and neither could the intermittency of the renewable generation. Several studies, like [50], also pointed to the benefits of interaction between those technologies to avoid overgeneration losses and mitigate the overload of transformers. Among the mitigation strategies are the use of management technologies for (1) optimizing the dynamics of EV charging through smart charging or load balancing (mitigating impacts on the electrical grid) and (2) integrating renewable energy sources with distributed energy resources. Noting that, when EVs operated with proper management in a V2G dynamic under a smart-charging profile, distributed energy resources can be considered to store the excess energy from renewable sources.

In agreement with this perspective, most recent studies also elaborate that it is of utmost importance that we start to address how to reduce those negative impacts, such as [54] where real life charging historical data from 10 EVSEs was collected to create a Multi Objective Optimization model for a decision-making scenario based on cost policies and other related parameters that could have a negative impact for companies and [55] where a deep analysis of the entire EV infrastructure, policies, and prospections was made.

But, even though all the previously mentioned studies bring different scenarios and analysis, showing the kinds of problems that we are likely to face with macro impact assessments, there is a lack of discussions about the micro perspective, with few elaborations on how the different physical components in the given structure interact with each other in practice, which brings us to more technical discussions about communication stability, compatibility, security, interoperability, integrity of data, and others. Thus, in this paper, we present a perspective that is focused on understanding the different elements that may be present in a practical environment.

To address these challenges, an architecture based on the Central Smart Charging proposed by the OCA [17] is presented and applied to integrate an EVSE into a network of different intelligent electrical devices, independent of the electrical grid and incorporating multiple energy resources (in addition to the charging station). Figure 4 illustrates the concept and general communication topology between the electrical system devices and the charging station. Voltage and current measurements in the feeder branches are obtained via IEC 61850, while the OCPP 1.6 protocol is used to send management data to the charging station.

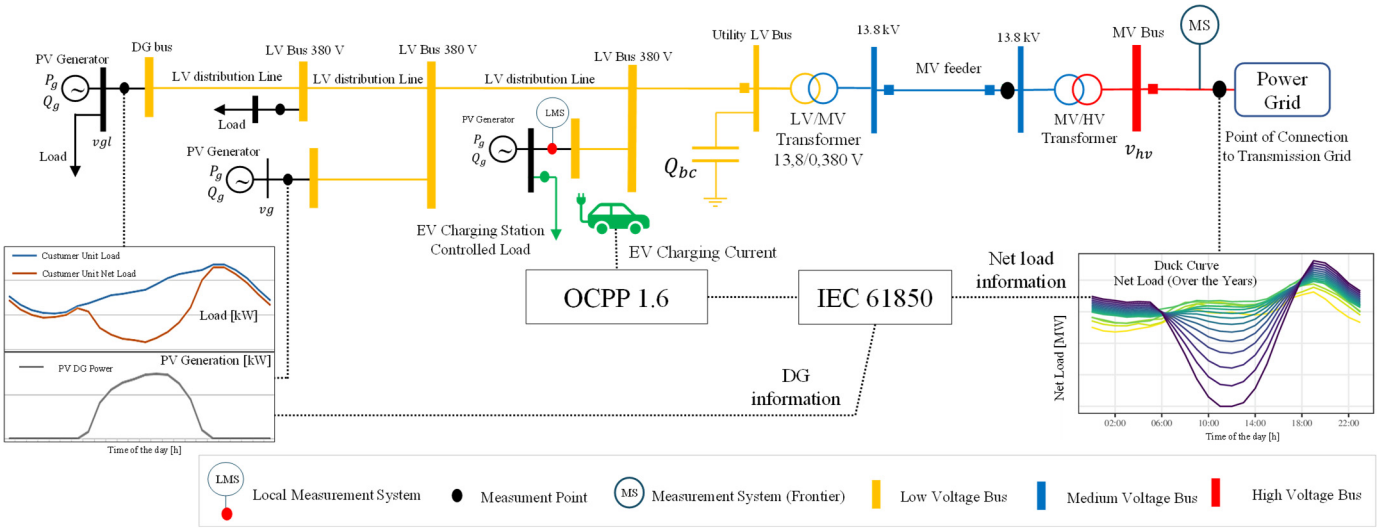


Figure 4. Schematic showing integration of electrical system information and charging stations with IEC 61850 and OCPP.

4.1. OCPP Request-Sending and -Receiving Algorithm

To differentiate the received messages used to create and send a response to the EVSE according to the protocol, it is necessary to implement an integration between a switch node, responsible for identifying the type of each command received by the CS (Central System), and function nodes, responsible for assembling the response payload to be sent. The resulting structure is represented in Figure 5. It is also through a function node that the message data is processed to be saved in the database.

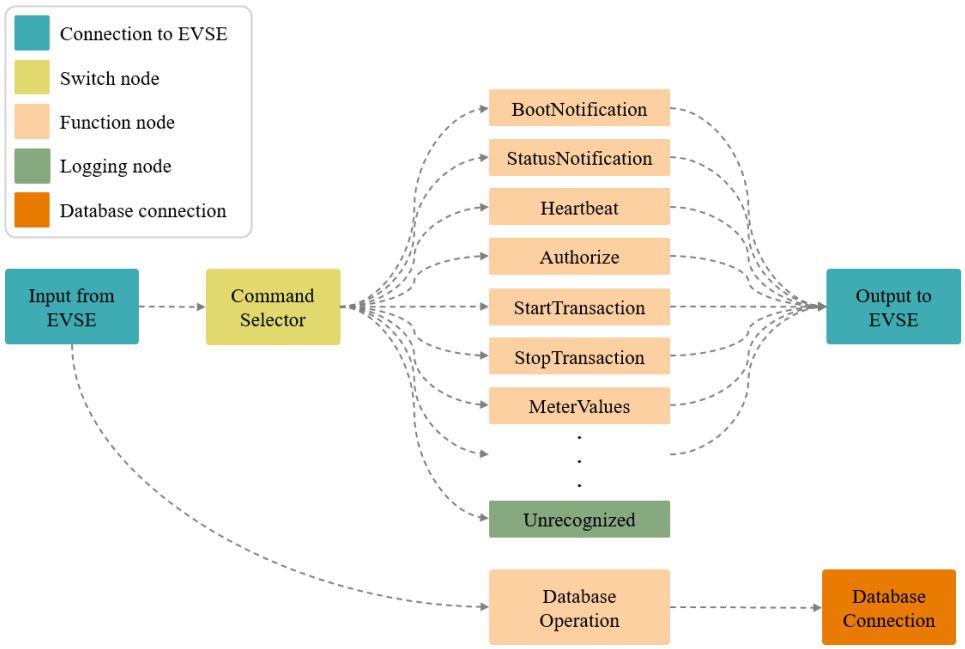


Figure 5. Flow structure created for processing messages sent by the EVSE.

4.2. Central Smart Charging

The management of multiple charging stations can be implemented using the OCPP framework defined as Central Smart Charging (CSS), illustrated in Figure 6. The CSS is directly responsible for all control of the EVSEs, capable of performing different types of control and limitations based on data sent by an external system, such as periods of

unavailability, reservation requests and load limits [17]. From this principle, a scenario of integrating multiple elements installed at an EV-charging station is analyzed. Considering the context of decarbonization, socio-environmental motivations, and the need to mitigate electrical impacts, it may become common in the future for charging stations to be built with the integration of renewable energy sources, energy storage, and grid integration, as described in projects [23,24], where the presented system includes photovoltaic generation, high-capacity batteries, and EV-charging stations.

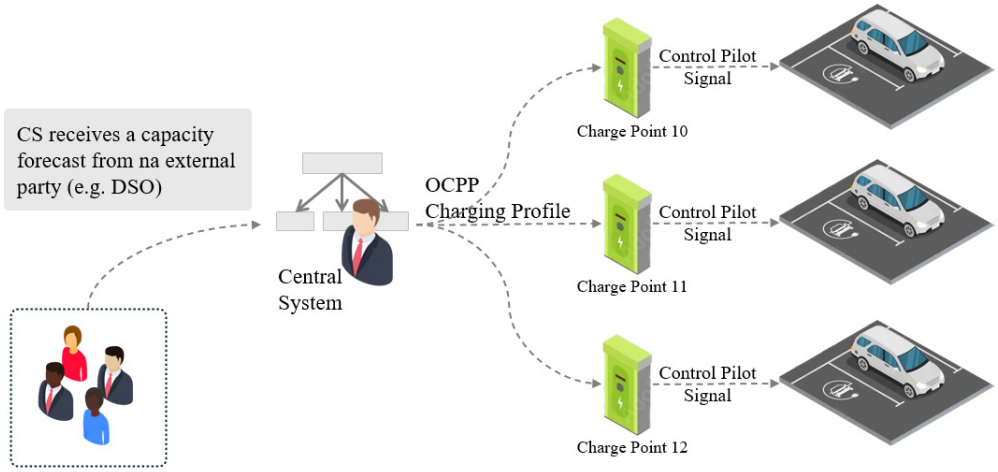


Figure 6. Central smart-charging general topology.

4.3. Storage and Mobility Laboratory–LAM Microgrid

The complete integration of a microgrid with multiple DERs and charging stations, considering configurations, protocol interoperability, and device parameterization, is a complex challenge. However, when fully operational, it effectively contributes to the formation of smart grids, mitigating impacts and allowing for the rational use of assets (transformers, transmission lines, feeders, etc.). Due to these complexities, to observe and experiment with the possible difficulties arising from the integration of energy resources, the implementation was carried out in a controlled environment. The developed methodology was applied in the Storage and Mobility Laboratory (LAM).

The microgrid equipment is illustrated in Figure 7. The facility contains one on-grid inverter (1), three off-grid inverters/chargers (2), two charge controllers (3), the battery storage system (4), a diesel generator (5), and an EV charging station (installed externally and has two 22 kW AC Type 2 plugs). All the equipment is physically connected into the electrical panel and (logical) integrated through compatible communication protocols.



Figure 7. LAM Microgrid—physical connection of equipment.

The SLM facility's general communication topology is represented in Figure 8, in a microgrid setup [27]. The installation includes energy resource equipment such as the Ongrid inverter, 19 kWp of photovoltaic modules, grid integration, lithium-ion batteries, and the EVSE. The LAM also features control and automation equipment, including a PLC and a centralized controller—the Cerbo GX—which is responsible for controlling the charging stations.

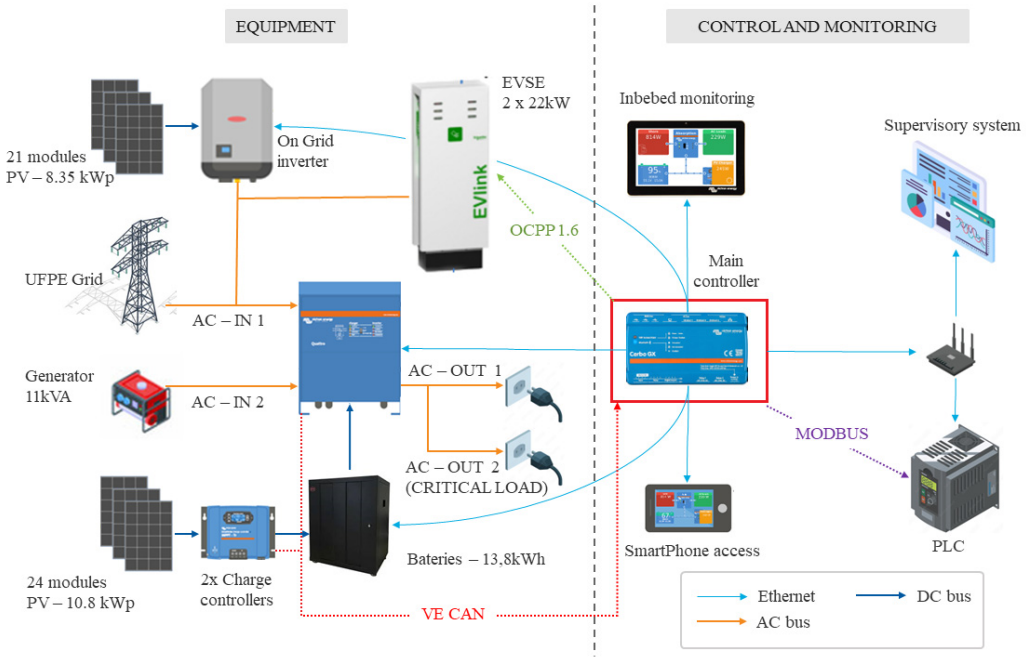


Figure 8. The equipment of the Storage and Mobility Laboratory—electrical connections and communication infrastructure.

5. Measurement Results and Implementation of Smart-Charging Strategy—Control by Charging Profile

This section describes the results of implementing a smart-charging strategy aimed at controlling the operation mode of a charging station. Initially, measurements were taken of a charging profile without the adoption of a demand management strategy (Section A). Then, the results of the operation with a management strategy acting as a limiter of the charging current are presented, either iteratively (Section B) or through a pre-configured charging profile (Section C).

5.1. Standard (Without Control) Charging Scenario

A database was created to store messages sent by the charger, as well as general measurements of electrical quantities, enabling the observation of the implementation results. Figure 9 illustrates the recorded voltage variations in each phase over several hours at one of the low voltage buses of the distribution system, obtained via IEC 61850. Figure 10 shows samples of measurements of instantaneous electrical quantities (voltage, current, and power factor in each phase). Figure 10 illustrates the power measurements on the LMS meter (in each phase) at the low-voltage bus connection of the charging station over six days of a week. The orange curve in Figure 11 represents a charge carried out without management. It is observable that, although it occurs during a period with photovoltaic solar generation, it represents a high-power demand in a short interval of time.

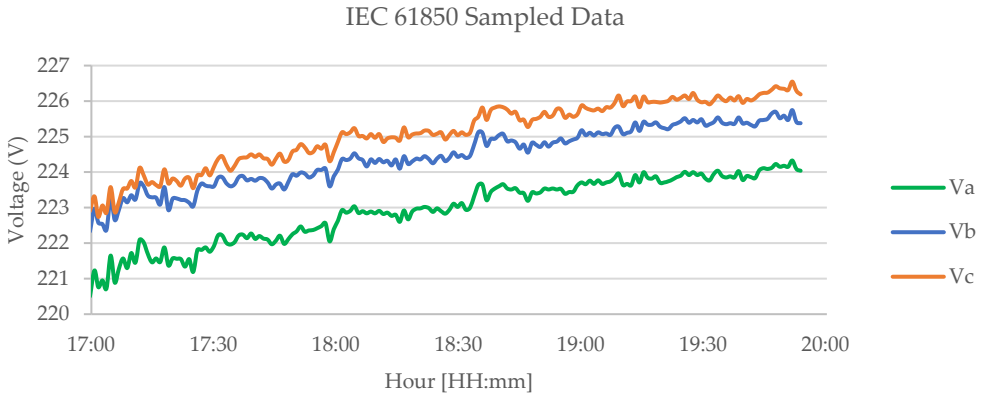


Figure 9. Measurements (voltage in each phase) at the low-voltage buses of the distribution system—obtained via IEC 61850.

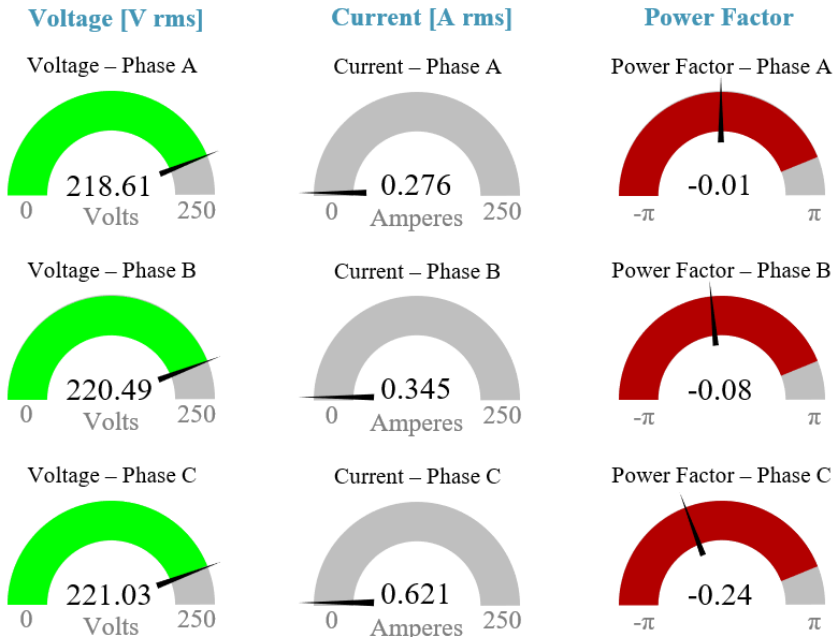


Figure 10. Measurements (voltage, current, and power factor) at the low-voltage buses of the distribution system—obtained via IEC 61850.

To demonstrate the system's functionality, data were collected initially from a complete charge without restrictions, with the EVSE offering its maximum current and no charging profile implemented, as shown in Figure 12. The graph presents values measured from a real charge with a 22 kW AC station. The curve represents the behavior of a charging method adopted for preserving the lifespan of lithium-ion batteries, called "constant current constant voltage—CC/CV mode" [56], which is applied due to the increase in the internal resistance of batteries at the end of the charge [57]. Studies show that not applying this method can cause accelerated degradation not only to the batteries but also to the vehicle's internal electronic systems [56,58].

The EV charger used was a 22 kW model, with an AC plug type 2 standard. During a charging session, the station sends current and voltage data. However, the vehicle's battery SoC data, as well as the values of internal parameters of the vehicle's AC/DC electronic converter, are not directly accessible via OCPP for the equipment used. Nonetheless, the current data during a charging session can be observed in Figure 12. Since the electric current is an available parameter, the management strategy is based on controlling the current supplied to the charging stations.

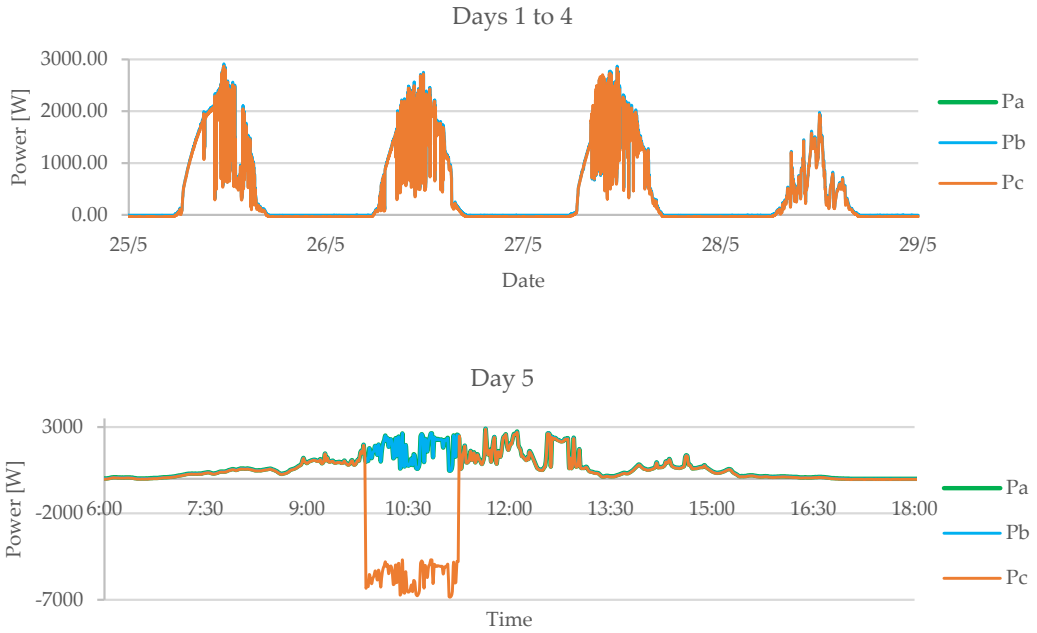


Figure 11. Power measurements on the LAM meter (in each phase) at the low voltage bus connection of the charging station—via IEC 61850.

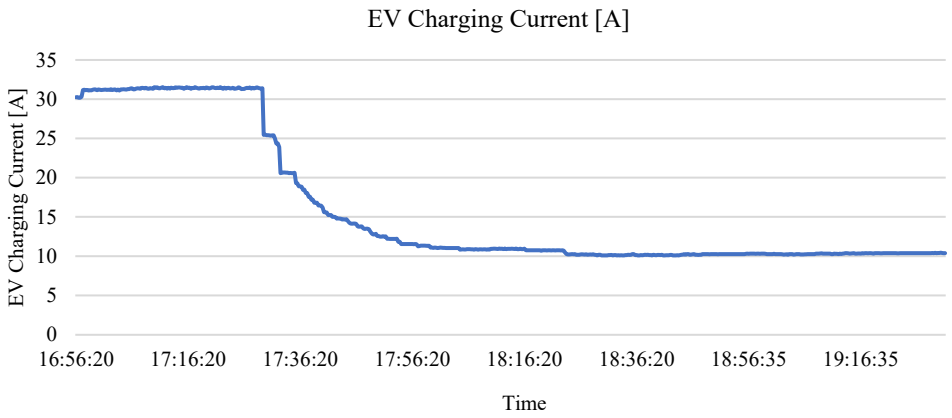


Figure 12. Charging current of an EV (measurement data)—obtained via OCPP 1.6 at the charging station (without current limitation).

5.2. Smart-Charging Strategy—Dynamic Limited Current Test Using OCPP Network

In [29,54,55], several approaches to control the current were mentioned; the majority of them were related to turning the charger on/off based on criteria such as time, variable pricing policies, or maximum available power output. This process is undesirable per se because of the possible negative impacts on battery longevity caused by the discrete charging process. Therefore, if the objective is to allow a full-time complex control of and, eventually, access to the energy stored in the EV batteries (V2G), as a consequence, it is necessary to develop strategies that allow for the EVSE to continuously charge with a controlled current limit, which also aggregates the benefit of avoiding the rapid temperature increase due to high currents on the batteries, culminating in the following proposed current control.

The main idea of the new current-controlling method proposed and described in this section was to suggest an algorithm capable of dynamically altering the current limit throughout the day and then collect the charging data from the EVSE operating under its

rules. The algorithm applies Equation (1), which is the scaling of a variable x with a known range $[X_{min}, X_{max}]$, to a new range $[a, b]$:

$$y(x) = (b - a)\frac{x - X_{min}}{X_{max} - X_{min}} + a \quad (1)$$

The management strategy is based on the idea of using historical data on electrical demand variation throughout the day to scale within a range of current limitations for the EVSE. From these values, at predefined intervals, such as every 10 or 30 min, the Central Charging Server (CCS) modifies the maximum current offered for charging, aiming to mitigate the impact of EV charging during peak hours.

The data used in the equation come from the current range defined by the EVSE manufacturer at LAM, between 12A and 32A [59], and the average daily consumption data for January 2024 in the state of California, USA, ranging from 3180 MW to 23657 MW, provided by the California Independent System Operator (California ISO) [60] (simulating the duck curve as a consequence of DG penetration). The result of using Equation (1) can be seen in Figure 13. It is observable that the maximum current value allowed for charging occurs during periods of lower power demand in the electrical system. Analyzing the results, the management strategy reduces the demand from EVs by up to 62.5% through the redistribution of consumption throughout the day. A disadvantage would be the increased charging time for EVs during peak hours, which, depending on the user's needs, could have a significant impact. This could justify, for example, a model where the maximum current at that time could be charged at a recharging price rate above the standard energy rate.

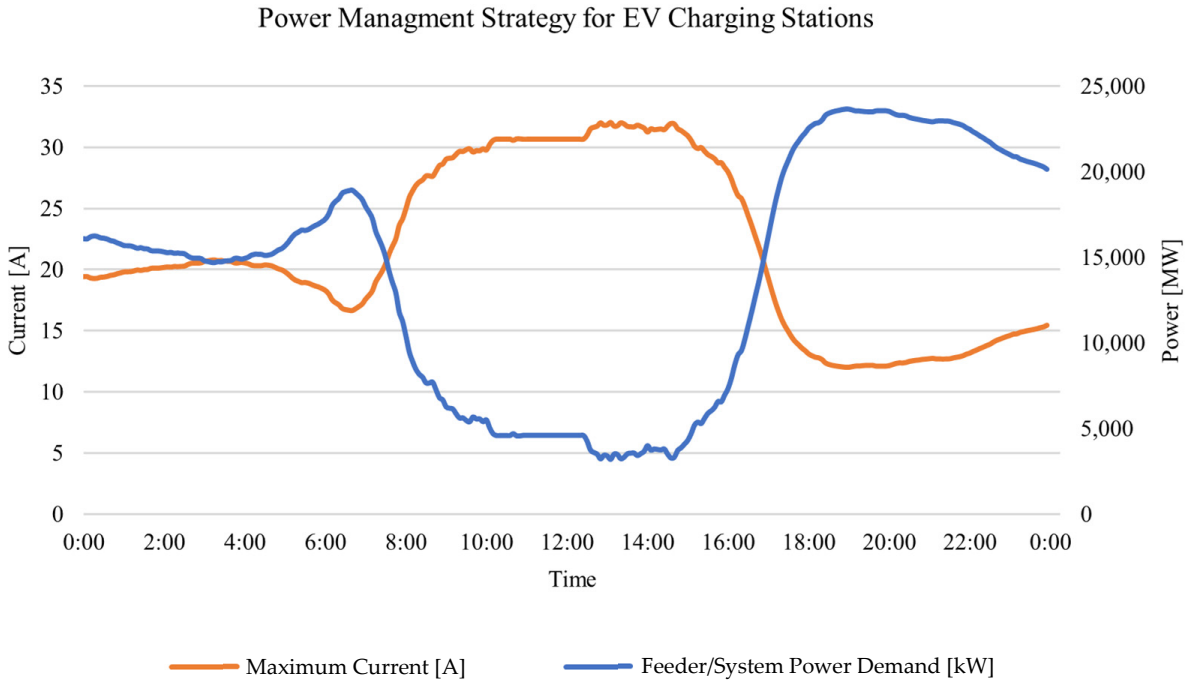


Figure 13. Maximum current calculated by scaling method.

The power limitation curve data were used to vary the range considering a future horizon of 1 h (updated every hour following the scaling as per Equation (1)). The calculated maximum current value was sent to the EVSE every 5 min, resulting in the data shown in Figure 14. As illustrated in the figure, it is evident that the proposed dynamic control of the current is feasible, and the algorithm and execution model can be generalized for other control modalities and purposes.

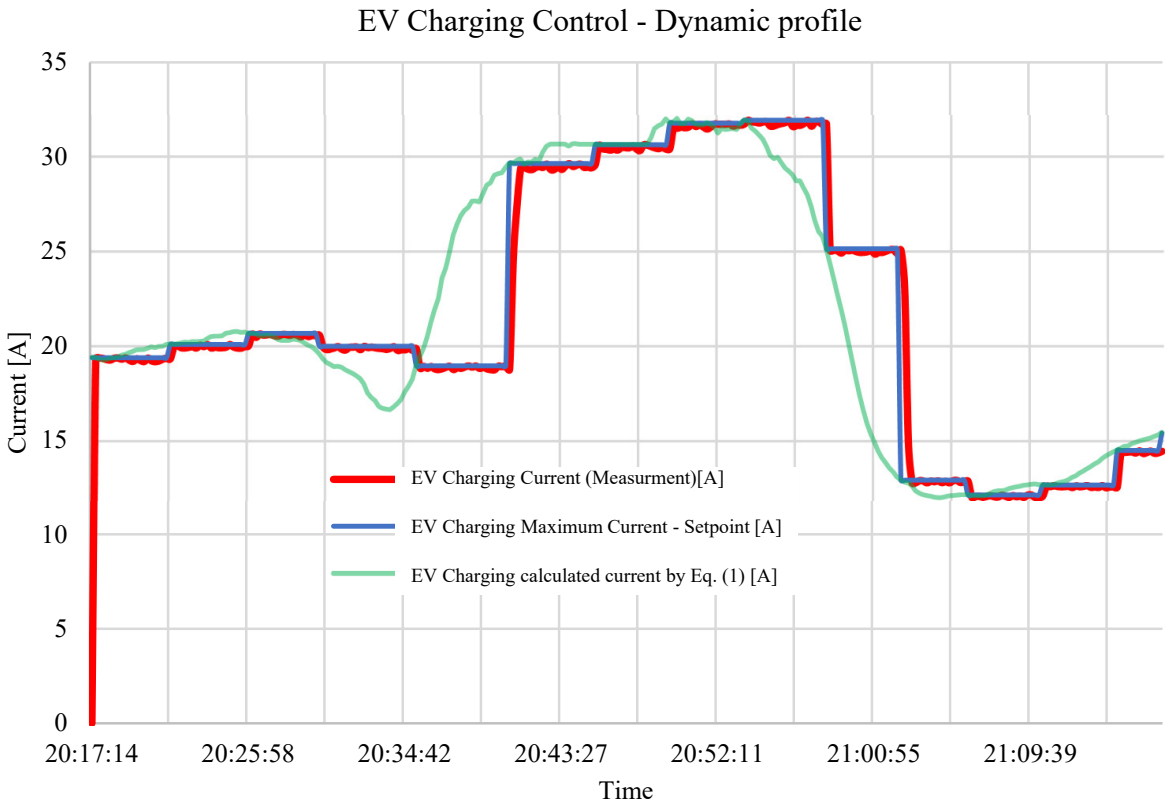


Figure 14. Result of the execution of the charging-control algorithm in a charging scenario, with scaling calculation updates within a 1 h horizon.

The current-limiting algorithm aims to increase the current available to chargers during periods of greater power availability in the feeder branches, following the pattern established by the duck curve. By using the inverse relationship given by Equation (1), the current supplied to the chargers is indirectly correlated with periods of high photovoltaic solar generation and low load demand. In Figure 13, it is possible to observe that the highest current magnitudes are made available to the chargers during the hours of the day associated with periods of higher solar irradiation. If the feeder branch also has, for instance, wind generation, the algorithm will also prioritize current availability for recharging during periods of higher wind power production (provided the load does not absorb the power generated by the wind).

5.3. Smart Charging: Control by Charging Profile

In this test, current control is defined based on a predefined profile. This control mode has results similar to those in the previous section, differing only in the methodology by which current limits are sent to the EVSE. In a practical example, daily consumption data were used to create a charging profile that applies the current limit hourly. The JSON sent to the EVSE is illustrated in Figure 15, and the resulting EVSE current limit throughout the day, collected with the OCPP GetConfiguration command, can be seen in Figure 16.

It is observable that even with control applied hourly, the apparent delay does not seem significant. However, this delay can still be minimized if control is performed every 10 min instead of every hour, for example. This curve, as in the previous case, demonstrates a potential mitigation of the impact of current from EV charging during peak demand periods on the grid.

```
msg.data = {
    "connectorInfo": ID,
    "csChargingProfiles": {
        "chargingProfileId": profileId,
        "stackLevel": 0,
        "chargingProfilePurpose": "ChargePointMaxProfile",
        "chargingProfileKind": "Recurring",
        "recurrencyKind": "Daily",
        "chargingSchedule": {
            "chargingRateUnit": "A",
            "chargingSchedulePeriod": [
                {
                    "limit": 19.40,
                    "startPeriod": 0
                },
                {
                    "limit": 19.79,
                    "startPeriod": 3600 // 1 hour
                },
                .
                . (limit and startPeriod for each hour of the day)
                .
                {
                    "limit": 13.15,
                    "startPeriod": 79200
                },
                {
                    "limit": 14.60,
                    "startPeriod": 82800
                }
            ]
        },
        "validFrom": "2024-01-01T00:00:00+00:00"
    }
}
```

Figure 15. Pseudo-JSON code executed to create the charging profile based on OCPP.

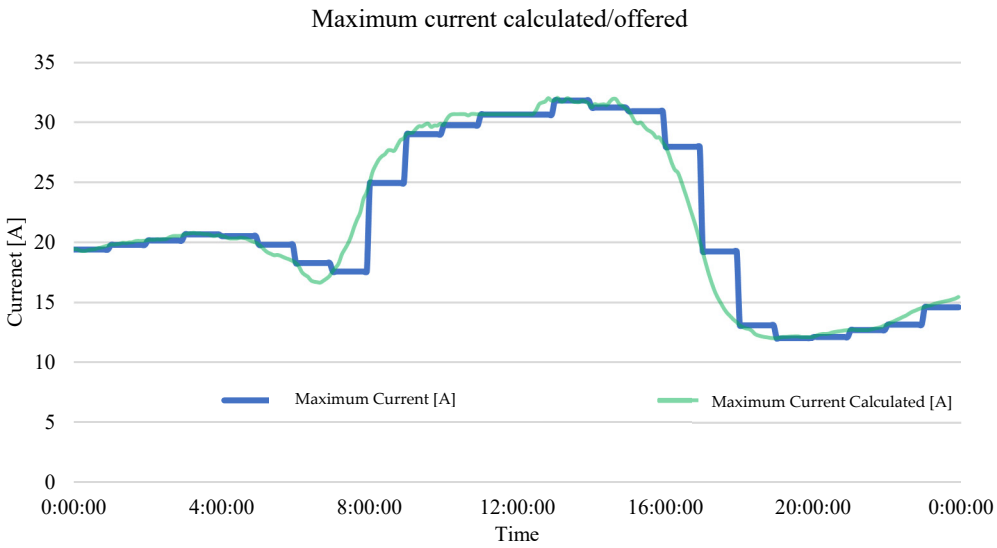


Figure 16. Charging-current limits defined by predefined charging profile based on the calculated values.

6. Smart-Charging Strategy—Dynamic Current Limited Using IEC 61850 Network

Currently, microgrids face significant interoperability challenges due to the diversity of existing and incompatible protocols and architectures [61]. Although a microgrid is linked to an electrical system domain, a wide variety of industrial protocols can be found, such as Modbus RTU and TCP, CAN-BUS, EtherCAT, Profibus, proprietary protocols, and analog instrumentation networks. The lack of interoperability observed in industrial environments is also present in environments involving distributed generation.

As described in the previous section, when EV chargers are added to a microgrid, an additional protocol is introduced: the Open Charge Point Protocol (OCPP), which stands out as an open standard for communication between chargers and charging management systems, often with various versions featuring incompatible functionalities [61]. The variety of protocols and lack of interoperability represent significant challenges for the integration

and efficient operation of these systems [62]. Devices with different protocols often need to be integrated into a single management system, requiring flexible solutions to overcome communication barriers.

In this context, IEC 61850 becomes a viable solution for standardizing all communication, given its established application in distributed generation (DER) environments and electric vehicle chargers [63]. IEC 61850 provides a standardized framework for data modeling and message exchange, facilitating communication between devices from different manufacturers. Its ability to abstract low-level communication details makes it applicable to a wide variety of devices and applications. Additionally, its object-oriented and event-driven approach allows for efficient integration of systems that include both traditional and modern devices [64].

The use of IEC 61850 in such a diverse domain composition with many distinct networks is also hindered by the high cost of the equipment that implements this standard. Therefore, one of the objectives of this article is to propose the use of low-cost microprocessor hardware as a viable solution for creating logically distributed smart microgrids, making them interoperable and self-descriptive, which are fundamental characteristics of this standard.

IEC 61850 uses abstract information models represented by classes and services, ensuring that devices from different manufacturers can communicate and operate in a distributed manner. Virtual entities represent specific functionalities of physical devices, facilitating the exchange of information and the execution of complex functions in a standardized manner. These entities are called logical nodes, and the grouping of logical nodes for implementing specific and well-defined functions forms a logical device. Therefore, a real IEC-compliant device contains embedded logical devices, communication services and protocols, and physical interface connections to the medium [65].

Efficient communication between logical nodes in physical devices is ensured by fast and reliable protocols such as Generic Object-Oriented Substation Events (GOOSEs), Sampled Value (SV), and Manufacturing Message Specification (MMS), which allow for real-time message exchange between devices and between devices and Supervisory Control and Data Acquisition (SCADA) systems, essential for dynamic control and monitoring in photovoltaic generation systems and electric vehicle charging. However, a crucial aspect is the modeling of the information to be transmitted over the network, as will be demonstrated below.

In the context of electric vehicle chargers and photovoltaic generation, IEC 61850 enables these systems to be monitored and controlled in real-time, optimizing energy production and efficiently integrating with the electrical grid, including measurements of solar irradiance, module temperature, voltage, current, and output power, among other relevant data [61–64]. For electric vehicle chargers, the standard allows for dynamic load management, adjusting the charging current based on energy availability and grid conditions, preventing overloads and ensuring safe charging. Chargers can coordinate with photovoltaic systems to efficiently use renewable energy, maximizing the use of solar energy for vehicle charging.

6.1. IEC 61850 Information Modeling Highlighting the Distribution of Intelligent Electronic Device (IED)

For this article, a communication architecture based on IEC 61850 is proposed, as illustrated in Figure 17. This architecture employs abstract models represented by classes, making the systems independent of various protocol stacks and ensuring interoperability between devices from different manufacturers. This is particularly crucial in microgrid environments with electric vehicle chargers, where the number of manufacturers and different protocols can be considerably large. Figure 17 shows the distribution of the main logical nodes required to control the current consumed by the EVSE. This setup presents a distributed control system where the first IED (power meter IED) performs the necessary electrical measurements, the second IED (controller IED) executes the control algorithm,

and the third IED (actuator IED) acts on the EVSE to maintain the power flow within the parameters defined by the control. Finally, a SCADA device monitors all variables in this distributed system.

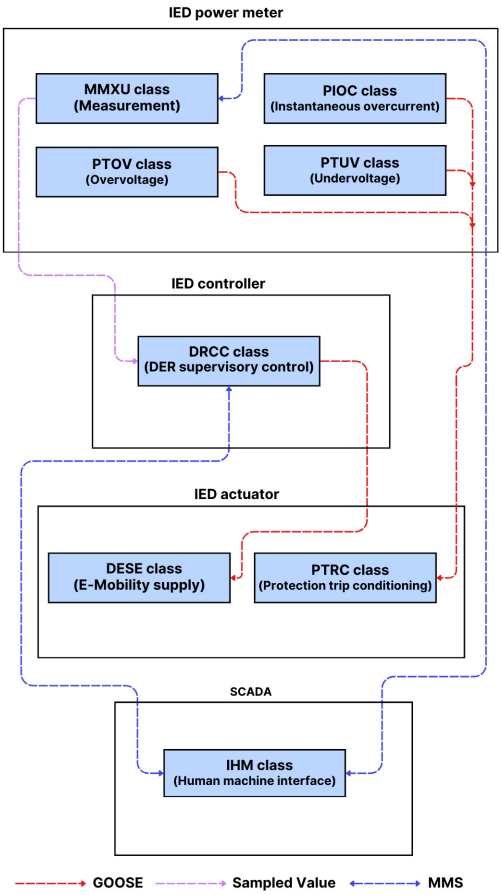


Figure 17. Communication architecture based on logical nodes.

It is important to note that the measurement equipment was entirely built in the laboratory for the implementation of this article, using the integration of an ESP32 for constructing the IED that performs system measurement and protection in case of overcurrent and overvoltage. This article will not explore how the measurement equipment was built.

It is also important to mention that both the control and protection of the system can be as complex as desired, including the IED interacting with the EVSE, utilizing various other logical nodes to perform functions not considered in this work. However, given that the primary objective of this article is to control the charging current in a distributed DER environment, the primary entities performing this task were selected.

6.2. Relationship Between Functions, Logical Nodes, and Physical Devices

In the IEC 61850 standard, the relationship between functions, logical nodes, and physical devices is fundamental for communication and automation in electrical systems. Functions are specific activities such as measurement, protection, control, automation, and monitoring necessary for operating and controlling devices within a domain. These functions are abstract and independent of the physical hardware, allowing flexibility in implementation.

Logical nodes represent these specific functions virtually within the automation system. Each LN groups a set of data and services related to a specific function. Identified by standardized names, LNs are also independent of the physical hardware, facilitating interoperability and modularity.

Physical devices refer to the physical hardware that hosts one or more logical nodes. These devices, known as Intelligent Electronic Devices (IEDs), can be protection relays, meters, and controllers, as well as microprocessor-based devices, the latter being developed and used in this article. Each physical device can contain multiple logical nodes, depending on the functions it needs to perform.

Figure 18 presents the functions used in the preparation of this work (the letter 'X' denotes the presence or absence of a Logical Node in the function composition). The relationship between functions, logical nodes, and physical devices is structured with abstract functions mapped to specific logical nodes. These logical nodes are then implemented in physical devices, where an IED can host multiple LNs, allowing for the simultaneous execution of various functions.

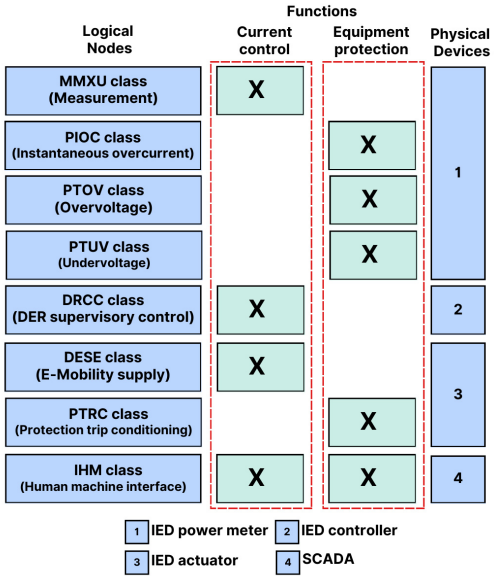


Figure 18. Current control and equipment protection function.

The actual implementation of physical devices involves executing the functions defined by the logical nodes, as well as the communication between these devices carried out through communication networks standardized by IEC 61850, such as SV, GOOSE, and MMS.

The separation between functions, LNs, and PDs provides flexibility in configuring and expanding automation systems, facilitating scalability. The modularity of logical nodes allows for the addition of new functions and devices without significant reconfigurations, promoting efficiency and reliability in managing operations in electrical systems. Understanding this relationship is essential for the successful implementation of automation systems that meet modern demands for efficiency and integration.

It is observed that the current control function proposed in this article is composed of four logical nodes, and the associated protection function is composed of five logical nodes. The entire project utilizes four physical devices, one of which is a SCADA for data supervision.

6.3. Implementation of Lib IEC 61850 in Smart Meter and Actuator IEDS

To integrate the libiec61850 library with the ESP32 microcontroller, several modifications to the library's source code were necessary. One significant change was the creation of a hardware abstraction layer, as the library originally supported only Linux, BSD, and Windows abstraction layers. This hardware layer simplifies the library's portability, allowing only specific functions to be redesigned and associated with the Espressif framework functions for IoT development (ESP-IDF).

In the ESP32 microcontrollers, publishers and subscribers for the GOOSE protocol, as well as MMS servers with logical nodes information, were implemented. The libiec61850 library allows the creation of MMS servers statically, using pre-existing XML configuration files, or dynamically, where creation occurs at runtime. For this setup, both logical nodes and their respective attributes were created dynamically, simplifying the configuration process for each device. In this application, the microcontrollers were not configured with timestamps, using the initial UNIX time instead.

This project demonstrates the efficient integration of ESP32 and Raspberry Pi devices using the IEC 61850 standard and protocols such as GOOSE and SV for controlling and monitoring an electric-vehicle-charging system. Using specific logical nodes and implementing libraries such as libiec61850 and Micro-OCPP ensures compliance with international standards and interoperability between heterogeneous devices. The described approach ensures safe, efficient, and intelligent management of charging operations, aligning with modern sustainability and energy efficiency requirements. Next, the operation of each IED in the project will be detailed. Figure 19 presents the network architecture used, as well as the devices, in a logical communication diagram that illustrates the data flow and their respective protocols.

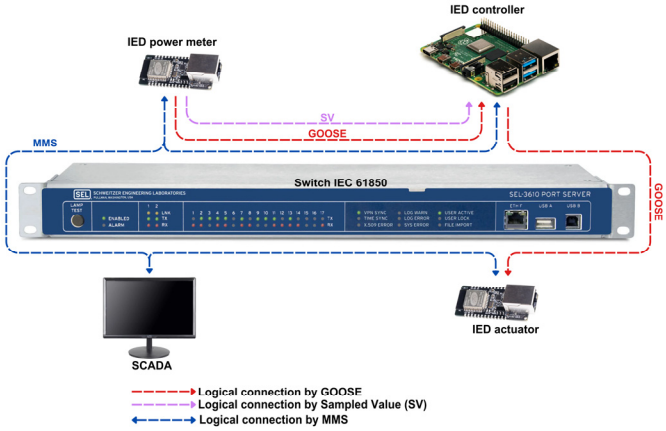


Figure 19. Network architecture.

6.3.1. Power Meter IED Implemented on ESP32

The first ESP32 was configured using the libiec61850 library to receive the main electrical measurements (voltages and currents, active, reactive, and apparent power) of the three-phase network through the logical node MMXU. Each of these quantities is represented by a data class of type WYE (Phase to ground/neutral related measured values of a three-phase system) within the logical node, specific for three-phase measurements. The three-phase current and power measurements were published on the network using the SV protocol, continuously making this information available for subscription by the control IED.

Additionally, this IED includes logical nodes related to electrical protection, such as instantaneous overcurrent protection through the logical node PIOC, and overvoltage and undervoltage protection with the logical nodes PTOV and PTUV, respectively. These logical nodes use a data class called ACT (Protection Activation Information), which can activate the protection either generally or specify the phase/neutral of the quantity. The protection signals will be published on the network using the GOOSE protocol, allowing for the actuator IED to perform the necessary protections.

6.3.2. Controller IED Implemented on Raspberry Pi

The single-board computer Raspberry Pi is responsible for subscribing to the analog current and power data from the measurement IED via the SV protocol, using them to perform control through a specific method. Since the library already has a defined

abstraction layer for Linux operating systems, it was only necessary to implement it via Node-RED, compiling and executing the source code through the "exec" and "daemon" nodes of the platform. Two pairs of "exec" and "daemon" were used: the first for the subscriber of the SAMPLED VALUES protocol and the second to create the control IED.

The logical node used in this IED is DRCC, responsible for detailing the control operation. The maximum power value obtained through control is then placed in an APC (controllable analog process value) data class present in this IED, whose variation will result in network publication via the GOOSE protocol. This will allow for the actuator IED to subscribe and send this new setpoint to the electric vehicle charger.

6.3.3. Actuator IED Implemented on ESP32

The actuator IED receives the protection data from the measurement IED and the power setpoint value from the electric vehicle charger via GOOSE subscription. The received setpoint value is stored in the "ChaPwrLim" (Charging Power Limit) attribute of the logical node DESE, specific to electric vehicle charging equipment. The received protection data are used in the logical node PTRC, which performs the trip operation to activate the protection breaker if necessary. Besides being configured with libiec61850, the second ESP32 was implemented with the Micro-OCPP library, enabling communication with a server using the OCPP (Open Charge Point Protocol). This protocol is used in electric vehicle charging stations to manage charging sessions and obtain real-time data on the station's operation.

6.4. Communication Protocols Parameterization, Compatibility Challenges, and Scalability

The adoption of OCPP 1.6 presents both advantages and challenges. One of the key advantages of OCPP 1.6 is its wide acceptance in the industry, particularly due to its support for functionalities such as smart charging and load management. However, with the introduction of newer versions, such as OCPP 2.0 and 2.0.1, additional functionalities have been introduced, including enhanced security features (e.g., secure authentication), greater communication flexibility, and improved vehicle-to-grid (V2G) interaction capabilities. Despite these improvements, there are compatibility challenges between OCPP 1.6 and the newer versions. For instance, OCPP 2.0 adopts a different communication model, which is not retroactively compatible with version 1.6. This may require infrastructure upgrades or the implementation of intermediary layers to ensure interoperability between versions. Furthermore, as alternative protocols, such as the ISO 15118 standard for V2G communication, continue to evolve, the industry may face additional interoperability challenges. In scenarios where charging stations or fleet operators must support multiple protocols (e.g., OCPP, IEC 61850, ISO 15118), the complexity of managing these interactions increases, requiring the implementation of adaptable gateway solutions or software frameworks based on the specific version in use. In this work, the choice to use OCPP 1.6 for the available charger in the laboratory was a practical decision. However, for new EV charging models that utilize more recent protocol versions, in certain contexts, it would be more appropriate to adopt OCPP 2.0.1 due to significant changes in key commands, such as 'StartTransaction' and 'StopTransaction' (present in version 1.6), which have been replaced by an authorization process ('Authorize') combined with the TransactionEvent command in version 2.0.1. Considering these changes, it would also be necessary to develop a library to support OCPP 2.0.1 to ensure future compatibility.

When the IEC 61850-based approach is applied, the proposed architecture becomes inherently distributed, with functions modeled by standardized logical nodes (LNs), which can be located in physically separated equipment from different manufacturers. The modular nature of the standard allows the architecture to scale without the need for significant modifications to the existing infrastructure, facilitating the addition of new equipment without major reconfigurations. IEC 61850-7-420 [66], which specifically addresses Distributed Energy Resources (DERs), covers various sources of distributed generation, such as solar photovoltaic generation, energy storage, cogeneration systems, as well as electric vehicles

and their charging systems. For each type of generation source, there is an appropriate set of logical nodes that can be used, enabling the seamless integration of new distributed generation sources. Moreover, the use of standardized protocols from the standard, such as GOOSE (Generic Object-Oriented Substation Event), SV (Sampled Values), and MMS (Manufacturing Message Specification), reduces the need for network conversion devices, even with the introduction of new manufacturers and their proprietary protocols. Thus, the scalability of IEC 61850 is further enhanced by the abstraction of communication layers, which simplifies the integration of new devices into different generation systems.

7. Conclusions

After evaluating the main concepts regarding EVs, it is possible to observe that despite the challenges of implementing EVs, primarily associated with the need for distributed control and supervision, they also offer solutions to upcoming challenges in the context of the energy transition to renewable energy matrices with a high presence of distributed energy resources.

It is important to note that, as a disruptive technology, there is still an ideological social barrier to be overcome by the market for the widespread adoption of electric vehicles. As initially reviewed in this work through the literature review, forecasting results can be affected by bias in the database, which, to many, might go unnoticed. From this perspective, it is crucial to continue fostering critical and scientific thinking so that through practical and theoretical verification of the study objects, effective conclusions and solutions for the presented challenges can be reached.

In recent years, there has been an accelerated growth in the technological dissemination of EVs. This period brings not only research and development demands but also market opportunities for new sectors, such as the creation and maintenance of infrastructure, which can particularly benefit from this work. In this context, this work revisits the theoretical aspects involving EVs and presents step-by-step implementations to share the necessary technical/practical knowledge for creating and maintaining the infrastructure.

It was possible to analyze that, in a somewhat more distant reality, there will be a significant demand for more advanced management of these EV fleets, which can be integrated with other technological solutions like microgrids and solar power generation, in order to create a sustainable, efficient, and functional electrical system as a smart grid. This work contributes by describing a practical case study involving control over an EVSE through the implementation of a Charging Server in a microgrid infrastructure. The desired control and supervision results were successfully achieved, both in terms of data collection and control to mitigate the impacts of EVSEs during peak energy consumption periods. Furthermore, by using the correct parameterizations according to OCPP 1.6, through different approaches, it is possible to generalize the applications for a context of control with multiple EVSEs and achieve a higher level of complexity in managing the charging of EV fleets.

One of the challenges of the proposed methods is the integration and coordination of communication systems for dynamic/iterative power control. As described in Section 6, several pieces of equipment are required to establish a robust communication network for implementing control via IEC 61850. Fortunately, more simplified implementations based on pre-established standards, where current control is configured based on a standardized curve and set directly via OCPP, can avoid the need for infrastructure developed for continuous data acquisition. For electrical systems in developing infrastructure and less available communication systems, the configuration proposed in Section 5.3 (Smart Charging: Control by Charging Profile) is more recommended, as the current control of the chargers is preconfigured.

The implementation of the dynamic current-limiting algorithm demonstrates a significant advancement in smart-charging technology, contributing to the efficient integration of EVs into the existing electrical grid while leveraging renewable energy sources. Future works should explore optimization of the algorithm and its application across larger EVSE

networks to fully realize the benefits of smart charging in the context of a sustainable energy ecosystem.

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

Funding: This work was supported by the Program of R&D of National Electricity Regulatory Agency (ANEEL) and CPFL Energy under PD-00063-3059/2019.

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

Acknowledgments: This research was funded by the Program of R&D of National Electricity Regulatory Agency (ANEEL) and CPFL Energy. This work is related to the project "PD-00063-3059/2019—Support Solutions for the Expansion of the Electric Vehicle Recharge Infrastructure: Charging Stations Integrated to Battery Technology and Photovoltaic Systems (PV). LAM (Storage and Mobility Laboratory) equipment was acquired partly with resources from project PA3026. The electric vehicles used for recharge testing and to obtain the measurements presented in this work were loaned by CPFL Energia. The manufacturer Moura Batteries financially contributed with financing resources for the acquisition of equipment. The researchers from ITEMM helped by setting up a proof of concept and supporting the structuring of the LAM equipment. The researchers from IATI - Advanced Institute of Technology and Innovation was responsible for socio-environmental and economic analyses. The authors would like to thank the CPFL group for technical and financial support with resources from ANEEL's R&D program. Furthermore, the authors would like to thank the anonymous reviewers and editor for their valuable comments and suggestions.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Kouridis, C.; Vlachokostas, C. Towards decarbonizing road transport: Environmental and social benefit of vehicle fleet electrification in urban areas of Greece. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111775. [CrossRef]
2. Schmidt, M.; Staudt, P.; Weinhardt, C. Decision support and strategies for the electrification of commercial fleets. *Transp. Res. Part D Transp. Environ.* **2021**, *97*, 102894. [CrossRef]
3. Kapustin, N.O.; Grushevenko, D.A. Long-term electric vehicles outlook and their potential impact on electric grid. *Energy Policy* **2020**, *137*, 111103. [CrossRef]
4. Chen, T.; Zhang, X.P.; Wang, J.; Li, J.; Wu, C.; Hu, M.; Bian, H. A Review on Electric Vehicle Charging Infraestructure Development in the UK. *Int. J. Sci. Res. Arch.* **2023**, *10*, 193–205.
5. Zhu, Y.; Liu, Y.; Liu, X.; Wang, H. Carbon mitigation and health effects of fleet electrification in China's Yangtze River Delta. *Environ. Int.* **2023**, *180*, 108203. [CrossRef]
6. Zamasz, K.; Stęchły, J.; Komorowska, A.; Kaszyński, P. The Impact of Fleet Electrification on Carbon Emissions: A Case Study from Poland. *Energies* **2021**, *14*, 6595. [CrossRef]
7. Glyniadakis, S.; Balestieri, J.A.P. Brazilian light vehicle fleet decarbonization scenarios for 2050. *Energy Policy* **2023**, *181*, 113682. [CrossRef]
8. United States Environmental Protection Agency. Greenhouse Gas Emissions. EPA, 5 June 2024. Available online: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed on 22 June 2024).
9. Meinrenken, C.J.; Lackner, K.S. Fleet view of electrified transportation reveals smaller potential to reduce GHG emissions. *Appl. Energy* **2015**, *138*, 393–403. [CrossRef]
10. JDruitt, J.; Früh, W.-G. Simulation of demand management and grid balancing with electric vehicles. *J. Power Sources* **2012**, *216*, 104–116. [CrossRef]

11. Open Charge Alliance. OCPP & IEC 61850: A Winning Team. Available online: https://openchargealliance.org/wp-content/uploads/2024/01/Whitepaper-OCPP-IEC-61850-a-winning-team-Report-No.-23-3107-08-09-2023-Version.-1.0.pdf (accessed on 27 October 2024).
12. Gerodimos, A.; Maglaras, L.; Ferrag, M.A.; Ayres, N.; Kantzavelou, I. IoT: Communication protocols and security threats. *Internet Things Cyber-Physical Syst.* **2023**, *3*, 1–13. [CrossRef]
13. *IEC 61850*; Communication Networks and Systems for Power Utility Automation—ALL PARTS. 2024. Available online: https://webstore.iec.ch/en/publication/6028 (accessed on 22 October 2024).
14. Xiong, Y.; Wang, B.; Cao, Z.; Chu, C.C.; Pota, H.; Gadh, R. Extension of IEC61850 with smart EV charging. In *2016 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*; IEEE: Melbourne, VIC, Australia, 2016; pp. 294–299.
15. Schmutzler, J.; Andersen, C.A.; Wietfeld, C. Evaluation of OCPP and IEC 61850 for smart charging electric vehicles. In Proceedings of the 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, Spain, 17–20 November 2013; IEEE: Barcelona, Spain, 2013; Volume 11.
16. Miranda, L.R.D. Norma Global De Comunicação Em Subestações—IEC 61850. In Proceedings of the XVII SNPTEE—Seminário Nacional de Produção e Transmissão de Energia Elétrica, Curitiba, PA, Brazil, 16–21 October 2005.
17. Open Charge Alliance. Open Charge Point Protocol 1.6. Open Charge Alliance, March 2019. Available online: https://openchargealliance.org/my-oca/ocpp/ (accessed on 22 October 2024).
18. Al-Alawi, B.M.; Bradley, T.H. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. *Renew. Sustain. Energy Rev.* **2013**, *21*, 190–203. [CrossRef]
19. Kotler, P.; Keller, K.L.; Yamamoto, S. *Administração de Marketing*, 15th ed.; Pearson Universidades: São Paulo, SP, Brazil, 2018; pp. 93–95, ISBN 978-65-5011-047-5.
20. Statista. Electric Vehicles—United States. Available online: https://www.statista.com/outlook/mmo/electric-vehicles/united-states (accessed on 22 October 2024).
21. Statista. Annual Passenger Car Sales in the United States from 1951 to 2022. Available online: https://www.statista.com/statistics/199974/us-car-sales-since-1951/#:~:text=U.S.:%20Annual%20car%20sales%201951-2022&text=The%20U.S.%20auto%20industry%20sold (accessed on 22 October 2024).
22. Shepherd, S.; Bonsall, P.; Harrison, G. Factors affecting future demand for electric vehicles: A model based study. *Transp. Policy* **2012**, *20*, 62–74. [CrossRef]
23. Oliveira, M.S.D.; Santos, C.C.L.D.; Castro, J.F.C.; Tavares, L.; Marques, D.; Rosas, P.A.C.; Medeiros, L.H.A.D.; Bradaschia, F. EV demand forecasting based on logistic growth method applied to infrastructure planning for fast charging allocation integrated with storage and solar photovoltaic energy system. In Proceedings of the CIRED Porto Workshop 2022: E-Mobility and Power Distribution Systems, Porto, Portugal, 2–3 June 2022; Volume 6.
24. Castro, J.F.C.; Marques, D.C.; Tavares, L.; Dantas, N.K.L.; Fernandes, A.L.; Tuo, J.; de Medeiros, L.H.A.; Rosas, P. Energy and Demand Forecasting Based on Logistic Growth Method for Electric Vehicle Fast Charging Station Planning with PV Solar System. *Energies* **2022**, *15*, 6106. [CrossRef]
25. Vasconcelos, S.; Castro, J.; Limongi, L.; Azevedo, G.; Rosas, P.; Medeiros, L.D.; Marques, D.; Fernandes, A.; Qi, J.; Tavares, L.; et al. Operation of EV charging station with a photovoltaic system to reduce the impact on the distribution grid. In Proceedings of the 27th International Conference on Electricity Distribution (CIRED 2023), Rome, Italy, 12–15 June 2023; pp. 3963–3967.
26. Castro, J.F.C.; Roncolatto, R.A.; Donadon, A.R.; Andrade, V.E.M.S.; Rosas, P.; Bento, R.G.; Matos, J.G.; Assis, F.A.; Coelho, F.C.R.; Quadros, R.; et al. Microgrid Applications and Technical Challenges—The Brazilian Status of Connection Standards and Operational Procedures. *Energies* **2023**, *6*, 2893. [CrossRef]
27. Martins, M.N.; Castro, J.; Marques, D.; Rosas, P.; Rissi, G.; Fernandes, A.; Luo, X.; De Medeiros, L.A.; Lima, A.; Brito, M.; et al. Assessment of battery energy storage system operating modes in a microgrid for electric vehicles charging. In Proceedings of the 27th International Conference on Electricity Distribution (CIRED 2023), Rome, Italy, 12–15 June 2023.
28. Assis, F.A.; Coelho, F.C.R.; Castro, J.F.C.; DonadoN, A.R.; Roncolatto, P.A.C.R.R.A.; Andrade, V.E.M.S.; Bento, R.G.; Silva, L.C.P.; Cypriano, J.G.I.; Saavedra, O.R. Assessment of Regulatory and Market Challenges in the Economic Feasibility of a Nanogrid: A Brazilian Case. *Energies* **2024**, *17*, 341. [CrossRef]
29. Green, R.C.; Wang, L.; Alam, M. The impact of plug-in hybrid electric vehicles on distribution networks: A review and outlook. *Renew. Sustain. Energy Rev.* **2011**, *15*, 544–553. [CrossRef]
30. Hudson, B.; Razeghi, G.; Samuelsen, S. Mitigating impacts associated with a high-penetration of plug-in electric vehicles on local residential smart grid infrastructure. *J. Power Sources* **2024**, *593*, 233961. [CrossRef]
31. Senol, M.; Bayram, I.S.; Campos-Gaona, D.; Sevdari, K.; Gehrke, O.; Pepper, B. Measurement-based Harmonic Analysis of Electric Vehicle Smart Charging. In Proceedings of the 2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA, 19–21 June 2024.
32. Sevdari, K.; Calearo, L.; Bakken, B.H.; Andersen, P.B.; Marinelli, M. Experimental validation of onboard electric vehicle chargers to improve the efficiency of smart charging operation. *Sustain. Energy Technol. Assess.* **2023**, *60*, 103512.
33. Vasconcelos, S.D.; Castro, J.; Gouveia, F.; Filho, A.; Buzo, R.; De Medeiros, L.; Limongi, L.; Marques, D.; Fernandes, A.; Chai, J.; et al. Assessment of Electric Vehicles Charging Grid Impact via Predictive Indicator. *IEEE Access* **2024**, 1. [CrossRef]
34. Ufa, R.; Malkova, Y.; Rudnik, V.; Andreev, M.; Borisov, V. A review on distributed generation impacts on electric power system. *Int. J. Hydrogen Energy* **2022**, *47*, 20347–20361. [CrossRef]

35. Landera, Y.G.; Zevallos, O.C.; Neto, R.C.; Castro, J.F.d.C.; Neves, F.A.S. A Review of Grid Connection Requirements for Photovoltaic Power Plants. *Energies* **2023**, *16*, 2093. [CrossRef]
36. Howlader, H.O.R.; Sediqi, M.M.; Ibrahimi, A.M.; Senjyu, T. Optimal Thermal Unit Commitment for Solving Duck Curve Problem by Introducing CSP, PSH and Demand Response. *IEEE Access* **2018**, *6*, 4834–4844. [CrossRef]
37. Denholm, P.; O'Connell, M.; Brinkman, G.; Jorgenson, J. *Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart*; National Renewable Energy Lab.(NREL): Golden, CO, USA, 2015.
38. California Independent System Operator. *What the Duck Curve Tells Us about Managing a Green Grid*; FAST FACTS, 2016; California Independent System Operator: Folsom, CA, USA, 2016.
39. Filho, A.V.M.L.; Vasconcelos, A.S.M.; Junior, W.d.A.S.; Dantas, N.K.L.; Arcanjo, A.M.C.; Souza, A.C.M.; Fernandes, A.L.; Zhang, K.; Wu, K.; Castro, J.F.C.; et al. Impact Analysis and Energy Quality of Photovoltaic, Electric Vehicle and BESS Lead-Carbon Recharge Station in Brazil. *Energies* **2023**, *16*, 2397. [CrossRef]
40. Ulbig, A.; Andersson, G. Analyzing operational flexibility of electric power systems. *Int. J. Electr. Power Energy Syst.* **2015**, *72*, 155–164. [CrossRef]
41. Denholm, P. Energy storage to reduce renewable energy curtailment. In Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012.
42. Denholm, P.; Hand, M. Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy* **2011**, *39*, 1817–1830. [CrossRef]
43. Navid, N.; Rosenwald, G. Market Solutions for Managing Ramp Flexibility with High Penetration of Renewable Resource. *IEEE Trans. Sustain. Energy* **2012**, *3*, 784–790. [CrossRef]
44. Bhat, R.; Begovic, M.; Kim, I.; Crittenden, J. Effects of PV on Conventional Generation. In Proceedings of the 47th Hawaii International Conference on System Sciences, Waikoloa, HI, USA, 6–9 January 2014; pp. 2380–2387.
45. Akrami, A.; Doostizadeh, M.; Aminifar, F. Power system flexibility: An overview of emergence to evolution. *J. Mod. Power Syst. Clean Energy* **2019**, *7*, 987–1007. [CrossRef]
46. Cioara, T.; Anghel, I.; Antal, M.; Crisan, S.; Salomie, I. Data center optimization methodology to maximize the usage of locally produced renewable energy. In Proceedings of the 2015 Sustainable Internet and ICT for Sustainability (SustainIT), Madrid, Spain, 14–15 April 2015; pp. 1–8.
47. Mohajeryami, S.; Schwarz, P.; Baboli, P.T. Including the behavioral aspects of customers in demand response model: Real time pricing versus peak time rebate. In Proceedings of the 2015 North American Power Symposium (NAPS), Charlotte, NC, USA, 4–6 October 2015.
48. Delgado, J.; Faria, R.; Moura, P.; de Almeida, A.T. Impacts of plug-in electric vehicles in the portuguese electrical grid. *Transp. Res. Part D: Transp. Environ.* **2018**, *62*, 372–385. [CrossRef]
49. Hu, J.; Morais, H.; Sousa, T.; Lind, M. Electric vehicle fleet management in smart grids: A review of services, optimization and control aspects. *Renew. Sustain. Energy Rev.* **2015**, *56*, 1207–1226. [CrossRef]
50. Dallinger, D.; Wietschel, M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3370–3382. [CrossRef]
51. *ISO 15118*; Road Vehicles—Vehicle to Grid Communication Interface—Part 20: Network and Application Protocol Requirements. ISO: Geneva, Switzerland, 2022. Available online: https://webstore.iec.ch/en/publication/26347 (accessed on 22 October 2024).
52. *IEC/TR 61850-90-7*; Communication Networks and Systems for Power Utility Automation—Part 90-7: Object Models for Power Converters in Distributed Energy Resources (DER) Systems. International Electrotechnical Commission: Geneva, Switzerland, 2023. Available online: https://webstore.iec.ch/en/publication/79121 (accessed on 22 October 2024).
53. Open Charge Alliance. Connecting the Ev Charging Industry. Available online: https://openchargealliance.org/ (accessed on 22 October 2024).
54. Erdogan, N.; Kucuksari, S.; Murphy, J. A multi-objective optimization model for EVSE deployment at workplaces with smart charging strategies and scheduling policies. *Energy* **2022**, *254*, 124161. [CrossRef]
55. Mastoi, M.S.; Zhuang, S.; Munir, H.M.; Haris, M.; Hassan, M.; Usman, M.; Bukhari, S.S.H.; Ro, J.-S. An in-depth analysis of electric vehicle charging station infrastructure, policy implications, and future trends. *Energy Rep.* **2022**, *8*, 11504–11529. [CrossRef]
56. Gao, S.; Chau, K.T.; Liu, C.; Wu, D.; Chan, C.C. Integrated Energy Management of Plug-in Electric Vehicles in Power Grid with Renewables. *IEEE Trans. Veh. Technol.* **2014**, *63*, 3019–3027. [CrossRef]
57. Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M. A review on the key issues for lithium-ion battery management in electric vehicles. *J. Power Sources* **2013**, *226*, 272–288. [CrossRef]
58. Kostopoulos, E.D.; Spyropoulos, G.C.; Kaldellis, J.K. Real-world study for the optimal charging of electric vehicles. *Energy Rep.* **2019**, *11*, 418–426. [CrossRef]
59. Schneider. EVlink Parking—EVlink City—EVlink Smart Wallbox—Charging Stations—Commissioning Guide (11). November 2022. Available online: https://www.se.com/br/pt/product-range/60850-evlink-parking/#documents (accessed on 22 October 2024).
60. California ISO. Today's Outlook. Available online: https://www.caiso.com/todays-outlook#section-net-demand-trend (accessed on 22 October 2024).
61. Hamdare, S.; Brown, D.J.; Cao, Y.; Aljaidi, M. EV Charging Management and Security for Multi-Charging Stations Environment. *IEEE Open J. Veh. Technol.* **2024**, *5*, 807–824. [CrossRef]

62. Martínez-Gutiérrez, A.; Díez-González, J.; Verde, P.; Perez, R.F.-G.A.H. Hyperconnectivity Proposal for Smart Manufacturing. *IEEE Access* **2023**, *11*, 70947–70959. [CrossRef]
63. Das, N.; Haque, A.; Zaman, H.; Islam, S.M.A.S. Exploring the Potential Application of IEC 61850 to Enable Energy Interconnectivity in Smart Grid Systems. *IEEE Access* **2024**, *12*, 56910–56923. [CrossRef]
64. Apostolov, A.; Muschlitz, B. Object modeling of measuring functions in IEC 61850 based IEDs. In Proceedings of the IEEE PES Transmission and Distribution Conference and Exposition, Dallas, TX, USA, 7–12 September 2003; Volume 2, pp. 471–476.
65. IEC. *Communication Networks and Systems for Power Utility Automation—Part 7-1: Basic Communication Structure—Principles and Models*; International Electrotechnical Commission: London, UK, 2007.
66. *IEC 61850-7-420*; Communication Networks and Systems for Power Utility Automation—Part 7-420: Basic Communication Structure—Distributed Energy Resources and Distribution Automation Logical Nodes. International Electrotechnical Commission: Geneva, Switzerland, 2021. Available online: https://webstore.iec.ch/en/publication/34384 (accessed on 22 October 2024).

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