DTU Library

Control and clustering of electric vehicle chargers for the provision of grid services

Sevdari, Kristian

Link to article, DOI:
10.11581/DTU.00000297

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

DTU Wind and Energy Systems
Department of Wind and Energy Systems

Control and clustering of electric vehicle chargers for the provision of grid services

Ph.D. Thesis

Kristian Sevdari

Risø, Denmark, November 2023

Control and clustering of electric vehicle chargers for the provision of grid services

Author
Kristian Sevdari

Supervisors
Mattia Marinelli, Associate Professor
Department of Wind and Energy Systems, Technical University of Denmark, Denmark

Peter Bach Andersen, Senior Researcher
Department of Wind and Energy Systems, Technical University of Denmark, Denmark

Dissertation Examination Committee:
Oliver Gehrke, Senior Researcher (Internal examiner)
Department of Wind and Energy Systems, Technical University of Denmark, Denmark

Marija Zima Bockarjova, PhD
Smart Cities and Solutions, ABB Electrification, Switzerland

I. Safak Bayram, Associate Professor
Department of Electronics and Electrical Engineering, University of Strathclyde, United Kingdom

Division of Power and Energy Systems (PES)
DTU Wind and Energy Systems
Frederiksborgvej 399, DTU Risø Campus
4000 Roskilde, Denmark
https://windenergy.dtu.dk/english

Tel:	(+45) 46 77 50 85
E-mail:	communication@windenergy.dtu.dk

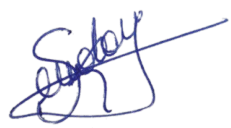
Release date:	November 2023
Class:	Public
Field:	Wind and Energy Systems
Remarks:	The dissertation is presented to the Department of Wind and Energy Systems of the Technical University of Denmark in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
Copyrights:	2020 - 2023
DOI:	10.11581/dtu.00000297

Preface

This thesis was prepared at the Department of Wind and Energy Systems of the Technical University of Denmark (DTU), in partial fulfillment of the requirements for acquiring the degree of Doctor of Philosophy in Engineering. The Ph.D. project was financially supported by the Danish research projects Autonomously Controlled Distributed Chargers-ACDC (EUDP grant number: 64019-0541) and Frederiksberg Urban Smart Electromobility-FUSE (EUDP grant number: 64020-1092).

The thesis summarizes the work carried out by the author during his Ph.D. project, between 1st December 2020 and 30th November 2023. During this period, he was employed as a Ph.D. student in the Division of Power and Energy Systems at DTU Wind and Energy Systems. The thesis is composed of a report, organized in five chapters, with seven attached scientific papers and one extended abstract. Six of these articles have been peer reviewed and published, whereas the remaining one and the extended abstract are currently under review.

Copenhagen, 30th November, 2023



Kristian Sevdari

Acknowledgements

The text in this manuscript describes nothing more than pure dedication and resilience to the cause of making a change in our society. However, this story goes back a long way. It starts with inhering the passion for natural sciences from my mother and the engineering mind from my father. Along the way, during eighth grade at ”Lasgush Poradeci” Middle School, my physics teacher mentioned for the first time that one day I will earn a Ph.D. 15 years later, this manuscript fulfills the dreams of the younger me. However, it would not be possible without the support of my family.

Furthermore, I express my heartfelt appreciation to my Ph.D. supervisors for their unwavering support, valuable guidance, and continuous encouragement. Mattia Marinelli, your expertise and mentorship have significantly shaped my research journey. I am sincerely grateful for the profound impact they've had on my academic and personal growth. Peter Bach Andersen, I appreciate the dedication, expertise, and inspiration you have generously shared, opening new doors, and illuminating a path of endless possibilities for me. Lastly, I would like to express my sincere appreciation to Bjørn Harald Bakken and Martha Marie Øberg, who welcomed me warmly at Statnett during my external research stay in Oslo. It was a pleasure to be part of constructive discussions, unwavering support, and the unique Norwegian perspective they provided, enhancing the overall quality of my research.

During my Ph.D. I had the pleasure to work on different projects (ACDC and FUSE), collaborating with multiple partners from academia and industry. I would like to thank all these partners with whom I had the pleasure of working and who had fruitful discussions and collaborations. I could not forget to thank all my previous and present colleagues in Risø and Lyngby, who in the past three years created an amazing work environment, both in the office and online. A special thanks goes to Andreas, Angelina, Chresten, Eva, Daniel A., Ha, Haris, Helle, Henrik, Jan, Jan Martin, Kai, Kristoffer, Lisa, Magnus, Mattia S., Mirko, Oliver, Simone, Tatiana, Tom, Tim, Tue, Yi and Zeenat with whom I had the pleasure to work and evolve as a researcher. I am grateful to Tim, Mirko, Kristoffer and Mattia S. for their valuable feedback on my thesis; to Magnus, Daniel A. and Olvier for their constant assistance during my time in the EV-LAB; to Lisa and Andreas for being role models and always ready to provide support; and to

Jacob Ø. for allowing me to skip the DTU hierarchy and supporting many of my initiatives. I am also grateful that I had the opportunity to supervise, and learn from, talented M.Sc. students. A big thanks goes to Aurora, Adelaida, Mari Halldis, Rasmus, Teis, Vasileios, and Valdemar. Thanks also to the colleagues I met during my external stay at Statnett - Market design and system utilization, who welcomed me and made me live a very enjoyable, yet productive, period of my Ph.D.

Ne nuk jemi asgjë tjetër përveç se pluhur kozmik.

Dedikuar familjes time Mirandës, Pëllumbit dhe Irisës.

Në kujtim të gjyshit Sulo dhe gjyshes Mirsi.

PER ASPERA AD ASTRA

Abstract

The transportation and power sectors are experiencing a paradigm shift. On the one hand, the transition away from fossil fuels in the transportation sector is paving the way for the emergence of electric mobility. On the other hand, the shift towards a sustainable power system necessitates novel approaches to power system operation and planning. Therefore, a synergy between electric mobility and renewable energy sources (RESs) can contribute significantly to the progress of both industries. In this context, the charging infrastructure serves as the link between the transportation and power sectors, encompassing both electrical and communication aspects. The prospects and hurdles of electrifying transportation hinge on the positioning, variety, utilization, and functionalities of this charging infrastructure.

To date, slow charging is by far the most widely utilized type of charging infrastructure for public and private charging sessions. Here, slow charging correlates with long vehicle parking times, allowing for better accommodating the charging energy demand in combination with the restrictions of the power grid.

This thesis investigates the potential for controlling electric vehicles (EVs) and AC chargers for the provision of grid services to benefit both the power and transport sectors. Research is focused on the AC charging infrastructure comprising electric vehicle supply equipment (EVSE) and the vehicle on-board charger (OBC). The coordination of such technologies is of paramount importance for the delivery of grid services in support of a RES dominated power system. The thesis is divided into three parts.

The first part discusses the transport-power sector coupling conundrum in a systematic way. The primary objective is to establish a connection between ancillary services and EV flexibility to aid system operators (SOs) and flexibility providers in understanding the role and optimal location of EV charging clusters in the power system. To attain this objective, a comprehensive review of ancillary services is imperative, taking into account the operational challenges of the power system. Among the diverse range of ancillary services, those that can be provided by the charging infrastructure are highlighted and classified into 12 geoelectric charging clusters. The second objective focuses on the EV flexibility supply chain and identifies seven actors regardless of geographical considerations. Here, it is important to highlight the functionalities required for EVSEs. Therefore, a smart EVSE is defined as an electric device that provides protection, communication, at least scheduling, and at most modulation, phase curtailment (3 to 1-phase switch), and phase switching for the EV charging process.

The second part continues with EVSEs and OBC control capabilities by transitioning from theoretical to practical ground. Since the OBC is responsible for the conversion from AC-to-DC current (charging the battery), the first research area addresses the efficiency and reactive power curves of the smart charging operation. Here, a methodology based on CANBUS/on-board diagnostics port (OBDII) readings to evaluate the characteristics of all commercial OBC is introduced and successfully validated with 38 different light-duty EVs models from the past 11 years. The results show that smart charging (by modulation) can increase charging losses from 1 to 10 %. The projections show an efficiency between 88-95% by 2030 and a saturation between 90-96% by 2035. Additionally, some models consume larger amounts of reactive power at lower currents or vice versa. Furthermore, the second objective focuses on developing and validating a method to measure the entire control loop speed (measurement-control action-EVSE-OBC) when delivering grid services. The findings indicate that OBC remains the bottleneck in providing faster grid services. Nonetheless, some automakers offer the possibility to achieve a control action of less than one second.

The third part centers around the utilization of flexibility through smart residential charging applications in Denmark and Norway. Both cases rely on real data. The Danish cases focus on simulations of behind-the-meter (BTM) applications with a novel autonomous distributed control architecture for EVSEs. The aforementioned approach seeks to enhance the overall charging experience for EV owners while aligning it with the support for the grid. The findings indicate that strategies incorporating price and emission signals not only achieve their intended objectives but also yield reductions in both costs and carbon dioxide (CO_2) emissions. Furthermore, the Norwegian case improves our understanding of residential charging coincidence factor (CF) by examining the correlations with i) temperature and seasonality, ii) time of day, iii) day and time of week. This study also conducts a comparative analysis between natural (normal) and smart charging behavior. Here, considering market synchronization, the study explores the influence of smart charging on power system operations. Such large-scale infrastructure could pose the risk of adverse instant power delivery effect, as simultaneous charging could potentially strain the grid and require substantial grid investments. Therefore, the solution to the implications of synchronization lies in improving optimization algorithms to better share the available power capacity of the grid. These algorithms can be improved by considering the efficiency curves mentioned above and improving the control loop speed.

Resumé

Transport- og energisektoren gennemgår begge et paradigmeskift. På den ene side åbner overgangen fra fossile brændstoffer i transportsektoren vejen for elektrisk mobilitet. På den anden side kræver skiftet til et bæredygtigt energisystem nye tilgange til drift og planlægning af energisystemet. En synergi mellem elektrisk mobilitet og vedvarende energikilder (RES) kan derfor bidrage betydeligt til fremskridt inden for begge brancher. I denne sammenhæng fungerer ladeinfrastrukturen som bindeleddet mellem transport- og energisektorerne og omfatter både elektriske og kommunikative aspekter. Mulighederne og udfordringerne ved elektrificering af transport afhænger af placering, sammensætning, anvendelse og funktionalitet af denne ladeinfrastruktur.

Indtil videre er langsom opladning langt den mest anvendte type til offentlige og private opladningssessioner. På disse lokationer er parkeringstiden længere end det egentlige behov for ladning, hvilket giver mulighed for bedre at imødekomme ladebehovet i kombination med begrænsningerne i elnettet. Denne afhandling undersøger potentialet for at styre elbiler (EV'er) og AC-opladere for levering af netværkstjenester til gavn for både energi- og transportsektorerne. Forskningen fokuserer på AC-opladningsinfrastrukturen, der omfatter udstyr til forsyningen af elektriske køretøjer (EVSE) og køretøjets onboard-oplader (OBC). Koordinationen af sådanne teknologier er af afgørende betydning for leveringen af netværkstjenester til at støtte et RES-domineret energisystem. Afhandlingen er opdelt i tre dele.

Den første del diskuterer transport-energisektorkoblingsdilemmaet på en systematisk måde. Det primære mål er at etablere forbindelsen mellem elnet systemydelser og fleksibilitets mulighederne i elbilsladningen for at hjælpe systemoperatører (SO'er) og fleksibilitetsudbydere med at forstå rollen og den optimale placering af elbilsladeklynger i energisystemet. For at opnå målet er en omfattende gennemgang af systemydelser afgørende, hvor de operationelle udfordringer i energisystemet tages i betragtning. Blandt de nødvendige systemydelser er dem, der kan leveres af ladeinfrastrukturen, fremhævet og klassificeret i 12 geoelektriske opladningsklynger. Det sekundære mål har fokus på forsynings kæden for udnyttelsen af elbilers fleksibilitet og identificerer syv aktører uden geografiske hensyn. Det er vigtigt at fremhæve de funktioner, som derved kræves af EVSE enhederne. Derfor defineres en smart EVSE som en elektrisk enhed, der giver beskyttelse, kommunikation, mulighed for alt fra planlægning til modulering, fasebegrænsning (3 til 1 fase skift) og faseskift for opladningsprocessen.

Anden del fortsætter med EVSE og OBC-kontrolfunktioner ved et skift fra teori til praksis. Da OBC'en er ansvarlig for AC til DC konverteringen til opladning af batteriet, beskæftiger det første forskningsområde sig med effektivitets- og reaktive effekt-kurver for den smarte opladningsprocess. Her introduceres en metode baseret på CANBUS/on-board diagnostikportens (OBDII) aflæsninger for at evaluere karakteristika for kommercielle OBC'er. Metoden valideres med succes for 38 forskellige elbilsmodeller lanceret over de sidste 11 år. Resultaterne viser, at smart opladning (ved modulering) kan øge opladningstabene fra 1 til 10 %. Prognoserne viser en forbedring af effektiviteten til mellem 88-95% inden 2030 og en mætning mellem 90-96% som opnås inden 2035. Derudover forbruger nogle modeller større mængder reaktiv effekt ved lavere strømme eller omvendt. Desuden fokuserer anden del på at udvikle og validere en metode til opmåling af forsinkelserne i hele reguleringssløjfen (måling-kontrolhandling-EVSE-OBC), når der leveres systemydelser. Resultaterne indikerer, at OBC'ens reaktion er den afgørende faktor for levering af hurtigere systemydelser. Nogle producenter understøtter muligheden for reaktion på mindre end et sekund.

Tredje del omhandler udnyttelsen af fleksibilitet gennem smarte hjemmelade-applikationer i Danmark og Norge. Begge tilfælde baserer sig på opsamlet data. Det danske case fokuserer på simulationer af bag-måler egetforbrugs (BTM) applikationer med nye autonome distribueret kontrolarkitekture for EVSE'er. Denne tilgang søger at forbedre den samlede oplevelse for elbilsejere, samtidig med at der udføres systemydelser for elnettet. Resultaterne indikerer, at strategier, der inkorporerer pris- og emissionsignaler, ikke kun opnår deres tilsigtede mål, men også medfører reduktioner i omkostninger og kuldioxid (CO2) emissioner. Derudover forbedrer analyser af den norske data vores forståelse af hjemmeladnings-sammenfaldsfaktoren (CF) ved at undersøge korrelationerne med i) temperatur og årstid, ii) tidspunkt på dagen, iii) dag og ugedag. Denne undersøgelse gennemfører også en sammenligningsanalyse mellem naturlig (normal) og smart opladningsadfærd. Her, ved at tage højde for markedssynkronisering, udforsker undersøgelsen indflydelsen af smart opladning på elnettets operationer. En infrastruktur af den størrelse kan udgøre en risiko for ugunstige effekter på elnettet, da simultan opladning potentielt kan belaste nettet og kræve betydelige investeringer. Derfor ligger løsningen på udfordringerne ved synkronisering i forbedring af optimeringsalgoritmer for at fordele den tilgængelige effektkapacitet i elnettet. Disse algoritmer kan optimeres med hensyn til de nævnte effektivitets-kurver og reguleringssløjfens hastighed.

Contents

List of Acronyms

AC	alternating current
AGC	automatic generation control
BMS	battery management system
BRP	balancing responsible party
BTM	behind-the-meter
CAPEX	capital expenditures
CF	coincidence factor
CPO	charging point operator
CSO	charging site operator
DC	direct current
DER	distributed energy resource
DK2	East Denmark grid region
DSO	distribution system operator
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCR	frequency containment reserve
FCR-D	frequency containment reserve for disturbance operation
FFR	fast frequency reserve
FRR	frequency restoration reserve
HAN	home area network
ICT	information and communication technology
KPI	key performance indicator
OBC	on-board charger
OBDII	on-board diagnostics port
OCPP	open charge point protocol
OPEX	operational expenditures
PF	power factor
PV	photovoltaic

PWM	pulse width modulation
RES	renewable energy source
RoCoF	rate of change of frequency
RR	replacement reserve
RT	research topic
SO	system operator
SOC	state-of-charge
ToU	time of use
TSO	transmission system operator
TyoU	type of use
V1G	unidirectional smart charger
V2G	vehicle-to-grid
VA	virtual aggregator

List of Figures

List of Tables

List of Publications

Papers included in the thesis

[P1] **K. Sevdari**, L. Calearo, P. B. Andersen, and M. Marinelli (2022). Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives. Renewable and Sustainable Energy Reviews, 167(December 2021), 112666.

[P2] **K. Sevdari**, L. Calearo, S. Striani, P.B. Andersen, M. Marinelli, and L. Ronnow. (2021). Autonomously Distributed Control of Electric Vehicle Chargers for Grid Services. Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021, 1–5.

[P3] S. Striani, **K. Sevdari**, L. Calearo, P. B. Andersen, and M. Marinelli (2021). Barriers and solutions for EVs integration in the distribution grid. 2021 56th International Universities Power Engineering Conference: Powering Net Zero Emissions, UPEC 2021 - Proceedings.

[P4] **K. Sevdari**, L. Calearo, B.H. Bakken, P.B. Andersen and M. Marinelli, (2023). Experimental validation of onboard electric vehicle chargers to improve the efficiency of smart charging operation, Sustainable Energy Technologies and Assessments, Volume 60, 103512.

[P5] **K. Sevdari**, S. Striani, P. B. Andersen, and M. Marinelli, (2022). Power Modulation and Phase Switching Testing of Smart Charger and Electric Vehicle Pairs. 2022 57th International Universities Power Engineering Conference: Big Data and Smart Grids, UPEC 2022 - Proceedings, 1–6.

[P6] **K. Sevdari**, P. B. Andersen, and M. Marinelli, (2023). "Aggregation and control of electric vehicle AC charging for grid services." Submitted to: IEEE Transactions on Smart Grid (under review).

[P7] M. H. Tveit, **K. Sevdari**, M. Marinelli, and L. Calearo, (2022). Behind-the-Meter Residential Electric Vehicle Smart Charging Strategies: Danish Cases. 2022 International Conference on Renewable Energies and Smart Technologies, REST 2022, 1–5, under-review.

[P8] A. Opstad, **K. Sevdari**, H. S. Nygård, B.H. Bakken, and G. Doorman, (2023). Flexibility from electric vehicles - residential charging coincidence factors in Norway. CIGRE General meeting Paris 2024, extended abstract.

Other publications

The following publications have been prepared during the course of the Ph.D. study, but are omitted from the thesis because they are not directly related to the primary research objectives, or partially covered by the selected papers.

Papers

[P9] M. Marinelli, **K. Sevdari**, L. Calearo, A. Thingvad, and C. Ziras (2021). Frequency stability with converter-connected resources delivering fast frequency control. Electric Power Systems Research, 200(July), 107473.

[P10] L. Calearo, C. Ziras, **K. Sevdari**, and M. Marinelli, (2021). Comparison of Smart Charging and Battery Energy Storage System for a PV Prosumer with an EV. Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: Toward a Carbon-Free Future, ISGT Europe 2021.

[P11] S. Striani, **K. Sevdari**, P. B. Andersen, M. Marinelli, Y. Kobayashi, and K. Suzuki, (2022). Autonomously Distributed Control of EV Parking Lot Management for Optimal Grid Integration. 2022 International Conference on Renewable Energies and Smart Technologies, REST 2022, I, 1–5.

[P12] S. Striani, **K. Sevdari**, M. Marinelli, V. Lampropoulos, Y. Kobayashi, and K. Suzuki, (2022). Wind Based Charging via Autonomously Controlled EV Chargers under Grid Constraints. 2022 57th International Universities Power Engineering Conference: Big Data and Smart Grids, UPEC 2022 - Proceedings, 1–6.

[P13] **K. Sevdari**, A. Islami, E. Haxhiraj, and E. Voshtina, (2022). A Data-Driven Assessment of the Electricity Demand-the Case of Albania. 2022 International Conference on Renewable Energies and Smart Technologies, REST 2022, I(mm), 1–5.

Technical reports

[R1] L. Calearo, **K. Sevdari**, and M. Marinelli, (2021). Status e-mobility DK. Technical University of Denmark.

[R2] **K. Sevdari** (2020). Electric vehicle chargers market outlook. DTU-Technical University of Denmark.

Datasets

[D1] **K. Sevdari** (2023). Albanian national consumption and weather conditions for 2016-2019. Technical University of Denmark.

[D2] **K. Sevdari**, and D. Marmullaku, (2023). Shapefile of European countries. Technical University of Denmark.

Co-supervision of Bachelor or Master's theses

[T1] M. H. Tveit, (2021). Electric vehicle charging flexibility for behind the meter applications. M.Sc. in Electrical Engineering, DTU, Denmark.

[T2] G. Fabbri, (2021). Charging Infrastructure for Shared Parking Facilities with Dynamic Load Sharing, B.Sc. in Electrical Engineering, DTU, Denmark.

[T3] T. K. Skogland, (2021). Charging flexibility from electric vehicles via autonomous chargers in a workplace (Master's thesis, NTNU, Norway).

[T4] A. G. Delgado, (2021). Design of Electric Vehicle Smart Charging Strategies to Maximize the Self-Consumption of o Hybrid Power Plant, M.Sc. in Electrical Engineering, DTU, Denmark.

[T5] B. Shan, (2022).Design of charging strategies with autonomous phase switching for an aggregation of EVs, M.Sc. in Electrical Engineering, DTU, Denmark.

[T6] V. Lampropoulos, (2022). Wind farm balancing via autonomously controlled electric vehicle chargers, M.Sc. in Electrical Engineering, DTU, Denmark.

[T7] A. Opstad, (2023). Mapping of residential consumer flexibility from electric vehicles and electric heating (Master's thesis, Norwegian University of Life Sciences, Norway).

[T8] M. Kaiser, (2023). Automating compatibility testing for Integration of charge points into an EV ecosystem, MSc in Electrical Engineering, DTU, Denmark.

[T9] M. E. Hansen, (2023). Implementation and test of the open charge point protocol in an autonomous charger for electric vehicles, M.Sc. in Electrical Engineering, DTU, Denmark.

Co-supervision of Special course

[S1] R. M. Knudsen, and V. C. Foss, (2022). Development of harmonized electric vehicle test and guidance on OCPP compliance for an electric vehicle smart charger. Special Course, MSc in Electrical Engineering, DTU.

PART I

Summary Report

CHAPTER 1

Introduction

1.1 Context and motivation

In recent years, numerous objectives and commitments have been established to specifically address the issue of climate change. The 2015 Paris Agreement mandates to restrain the global temperature rise to below 2°C above pre-industrial levels and striving for carbon neutrality by the second half of the current century [1]. The power and transport sectors account for respectively 40% and 23% of the global energy-related CO2 emissions [2]. Hence, the transition from fossil to renewable-dominated energy sources and electrification of transportation provides the much-needed cross-sector synergy that can drive the decarbonization and increase the social benefits.

The operation and planning of the power system are challenged by the increasing penetration of intermittent renewable energy sources (RESs) and new distributed technologies [3]. These challenges can be classified as i) Adequacy and security of supply (having enough generation to cover peak demand at any time) [4], ii) Power system stability (the ability of the power system to regain the operating equilibrium state after experiencing a physical disturbance) [5], [6], and iii) Power system resilience (the ability of the system to react to extreme or catastrophic events) [7]. Therefore, controlling the demand side can provide the necessary flexibility to the power system. This controlling action can benefit the power system in two ways: i) balance the needs of the operator, and ii) substitute or postpone the grid upgrades.

Effective management and coordination of the electric vehicles (EVs) charging process can provide flexibility on the demand side to the power system, leveraging the flexibility in time of slow charging [8]. Some figures suggest that by 2050, there will be a flexibility potential from EVs of 878 GW out of 1648 GW [9]. That being said, e-mobility has two main requirements to be met, energy requirements and instantaneous power requirements [10]. Although the energy needs of e-mobility are not a challenge [11], EVs rapid growth has an adverse instantaneous power delivery effect; the simultaneous charging can potentially harm the grid or require large investments in upgrading it [12]. Therefore, 'smart EV charging' is being investigated as a solution to maximize flexibility and mitigate the impact of the adoption of mass e-mobility [13].

The smart charging solution can be looked at from three perspectives. First, the coordination framework of multiple units or clusters with chargers in combination with other resources or loads in the power system without compromising the user's needs. Due to their large geographical spread, it is of paramount importance to understand charging clusters and grid service coordination opportunities [14]. Second, the control and efficiency of the smart charging process. Previous work has highlighted the importance of faster control speed, which benefits the power system [15]. Smart AC charging is based on the IEC 61851-1 standard [16] for communication between electric vehicle supply equipment (EVSE) and on-board charger (OBC). However, the IEC 61851-1 standard control quality and speed requirements are not designed to deliver fast grid services. It is then up to EVSE manufacturers and automakers to design state-of-the-art equipment that can qualify for grid service applications. In addition, OBC technology has not yet matured enough for a large window of efficient operation [17]. In other words, EVs, albeit being the largest loads in the households, are not labeled according to European efficiency regulations. Third, the economic and technical results of smart charging algorithms. Despite many investigations underlining the economic viability of combining smart charging algorithms with electricity markets [18]–[20], the synchronization with electricity market prices has changed the natural EV charging coincidence factor [21], leading to higher values [22], with a consequence on grid loading peaks [23]. Hence, it is crucial to correctly balance the smart charging optimization algorithms with the grid requirements.

1.2 Research objectives

This thesis investigates the control and coordination of AC smart charging in combination with renewable energy and power system needs. The research topic was extensively covered during two Danish research projects ACDC (focusing on the design of a novel smart charger) and FUSE (focusing on the uptake and coordination of smart charging in a urban environment). Figure 1.1 presents a graphical visualization of the research topic using artificial intelligence.

Figure 1.1: Graphic visualizing the PhD topic using artificial intelligence.

Moreover, this thesis deals with three overarching research topics (RTs) that can be summarized as follows.

- RT1: Coordination framework for the smart charging process that involves all relevant actors.
- RT2: Control loop for the smart charging process that is focused on efficiency and speed.
- RT3: Smart charging economic results for the end user and technical implications for the power grid.

These three research topics are addressed by the seven independent scientific publications presented in [P1]-[P8]. A visualization of the Ph.D. research investigation is provided in Figure 1.2. From left to right (Figure 1.2), the components of the power system and the most relevant actors are described to understand the investigation of the research and how the scientific publications interact with each other.

The first topic contributes to defining a framework for delivering grid services from e-mobility. In particular, it distinguishes power system needs, charging clusters, actors, barriers, and technical possibilities for providing grid services from EVs. Another contribution is the comprehensive classification of smart charging technology and state-of-the-art features.

The second topic delves into smart charging technology focused on the control of EVSE-OBC combination. This part is mostly concentrated on the experimental validation and field testing of the technology. The smart charger or smart EVSE serves as the interface between the vehicle and the power grid. The Ph.D. contributions are centered around i) field testing and modeling the EVSE state-of-the-art control features, ii) measuring and modeling the delays for the entire control loop, iii) experimental validation of the OBC technology in relation to smart charging, and iv) designing a novel autonomous distributed control architecture for the smart charging operation.

The third topic quantifies the economic viability of smart charging strategies in the Danish landscape. In addition, it provides insights into the real-world smart charging application from Norway. In particular, one main contribution of this part is the correlation of the coincidence factor (CF) for the charging process with market incentives and meteorological conditions.

Finally, based on the research findings, the thesis draws conclusions on the feasibility, benefits, and drawbacks of the smart charging operation. In addition, perspectives on future research directions are presented.

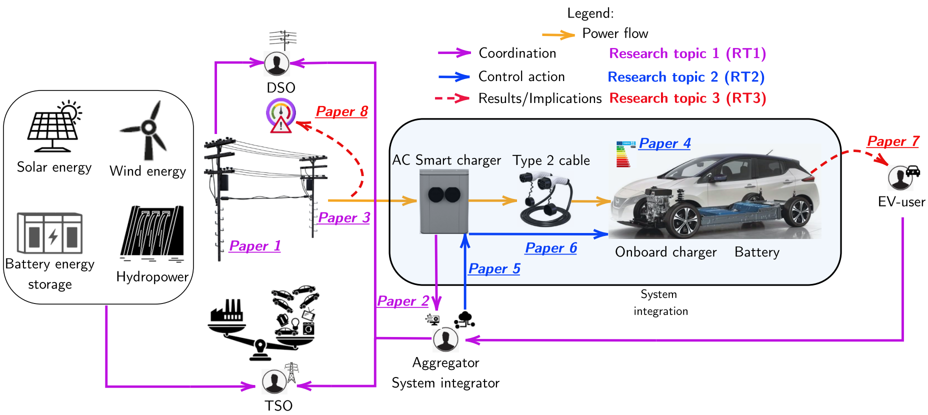


Figure 1.2: Visualization of the research investigation.

1.3 Thesis outline

The thesis is structured in two parts. Part I serves as a comprehensive summary report, establishing the thematic framework for the scientific publications and emphasizing their principal contributions and discoveries. It is organized into five chapters: the introduction, three technical chapters, and a conclusion. Part II encompasses the six scientific publications and an extended abstract integrated within the thesis. Subsequently, a thematic overview of the subsequent chapters of Part I is provided.

Chapter 2 describes the framework for providing grid services with EVs. The chapter begins with a comprehensive overview of the current state-of-the-art in EVSE technology (**Paper [P1]**) and introduces a novel EVSE autonomous distributed control architecture developed in the ACDC project **Paper [P2]**. Furthermore, the chapter continues with **Paper [P1]** that reviews different types of ancillary services and the challenges system operators face in operating a power system with a high penetration of RESs. It then discusses the potential of EVs to provide ancillary services, and the different ways in which EV charging clusters can be managed to provide these services. Subsequently, regulatory and technological barriers (**Paper [P3]**) are discussed. The chapter concludes by identifying the key technical challenges that must be addressed to enable EVs to provide a wider range of ancillary services.

Chapter 3 continues the investigation of smart charging technology by transitioning from theoretical to practical ground. Moving forward, in order to provide grid services with EVs, one should take into account the efficiency of OBC (**Paper [P4]**) and the relevant communication and reaction delays (**Paper [P5]** and **[P6]**). First, the experimental work is focused on the efficiency of smart charging **Paper [P4]**. The main contribution is the testing and validation of a method for investigating EV OBC via the OBDII port. The results include the charging efficiency and reactive power characteristics of 38 different EV models from the last 11 years. This data set is of paramount importance for smart charging optimization algorithms. Using a Tesla Model S P85, Renault Zoe, and Nissan LEAF, **Paper [P5]** evaluates differently controlled (centralized and distributed) smart chargers against the IEC 61851 standard. Being representatives of the state-of-the-art, both chargers exceed IEC standard requirements and offer new grid service possibilities. However, the bottleneck for providing faster grid services is located in the EVs OBC. Therefore, **Paper [P6]** developes a methodology to precisely measure (in milliseconds) the delays in the control loop between the charger operator, EVSE, and OBC. The results highlight the possibilities of closing a control loop in a second time frame. The experimental testing considers centralized and distributed EVSE control architectures.

Chapter 4 shifts the focus to the economic viability of smart charging strategies. **Paper [P7]** presents results of the implementation of smart charging strategies in Danish families for two years (2020 and 2021). The designed strategies are focused on the end user, maximizing their economic benefits while reducing the impact on the grid and emissions. However, such smart charging strategies can create avalanche effects by synchronizing the end-user charging behavior. Thus, multiplying the charging peak at a specific synchronization time. This challenge is investigated in **Paper [P8]** by looking at CFs of residential charging in Norway. Historical data show that there is a significant difference between normal and smart charging behavior.

Chapter 5 provides a conclusion summarizing the main contributions and findings of the thesis and describes future research directions.

CHAPTER 2

Flexibility from e-mobility

2.1 AC charging technology

The realm of EVs has evolved in the recent years, with a notable focus on the charging technology. The development and deployment of EVSE for alternating current (AC) charging played a pivotal role in shaping the infrastructure for electric vehicles. This infrastructure encompasses the charging stations, connectors, and associated technologies that facilitate the transfer of electrical energy from the grid to the EV's battery. Understanding the nuances of AC charging technology is essential to understand the efficient and convenient charging options available to EV owners. In this section, we discuss the fundamental aspects, benefits, and challenges associated with the AC charging technology for EVs. The components required for AC charging are: i) EVSE, ii) Type 2 cable, and iii) EV. Table 2.1 describes the AC charging levels based on the IEC and SAE J standard [24]. It is possible to visually connect the European and US Level 1 with ”Granny cable” charging, and the rest with the common ”wallbox” or EVSE (see Fig. 2.1).

Table 2.1: AC charging level according to IEC 61851 and SAE J1772 [24].

Standard	**Type**	**Connection**	**Power [kW]**	**Max current [A]**
IEC 61851 (European)	Mode 1	1 phase	3.68	16
	Mode 2	1 or 3 phase	22	32
	Mode 3	3 phase	>22	>32
SAE J1772 (US)	Level 1	1 phase	3.3	12
	Level 2	1 or 3 phase	14.4	32

2.1.1 Onboard charging technology

Figure 2.1 presents a detailed explanation of the components. When an EV is connected to an AC charging station, the OBC within the vehicle converts the incoming AC power to direct current (DC) to recharge the battery. EVSE is responsible for communicating, via the charging cable, the maximum charge current allowed to the vehicle. However, it is the EV battery management system (BMS) that controls the OBC operation and decides the final charging current according to the needs of the battery pack. Therefore, two technologies are central for controlling the AC charging process, the OBC and the EVSE.

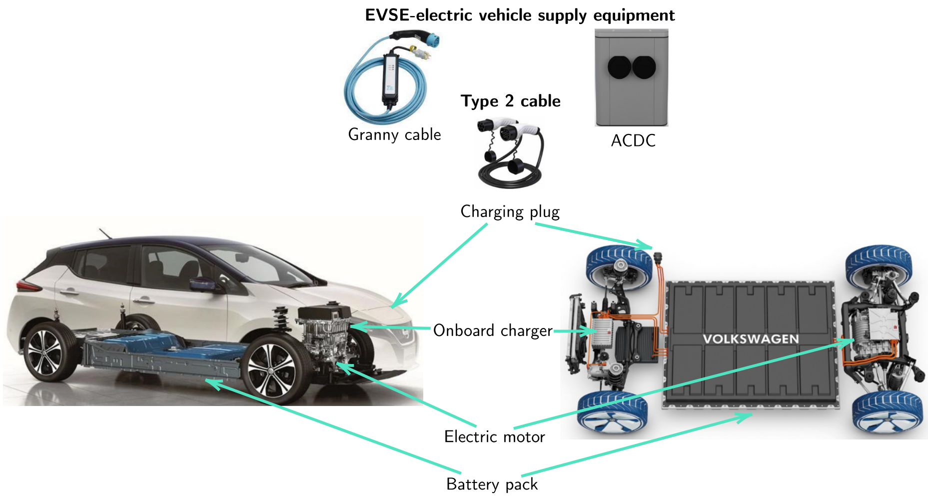


Figure 2.1: EV AC charging technology overview.

Two types of onboard chargers are present, and a detailed explanation of both technologies will follow in Chapter 3. The first one is the "dedicated" OBC, built as a standalone unit for the purpose of supplying the high-voltage battery pack and vehicle auxiliaries. The second one is the "integrated" OBC, which is combined to the electric motor of the vehicle. Here, the electric motor windings serve as an inductor for the OBC. The "dedicated" technology is more widespread than the "integrated" one. Figure 2.2 provides a typical block diagram description for the OBC.

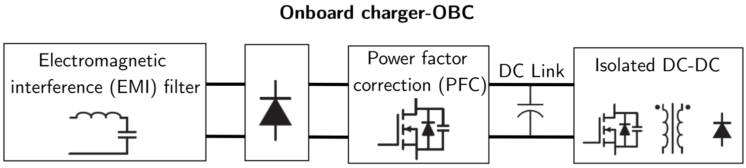


Figure 2.2: OBC typical block diagram reproduced from [25].

2.1.2 EVSE charging technology

Moreover, based on the work of **Paper [P1]**, the following sections define the EVSE charging technology and control topologies. Figure 2.3 visualizes the differences between a dumb (not controllable) EVSE and smart (controllable) EVSE.

A *dumb EVSE* is a device comprised of circuit breakers, relays, and voltage oscillator, which maintains a constant control pilot duty cycle to charge the EV. The scheduling devices outside the dumb EVSE (on the grid and EV side) can turn on or off charging process. In addition, it illustrates a smart behavior from the user side, even though users own a dumb EVSE.

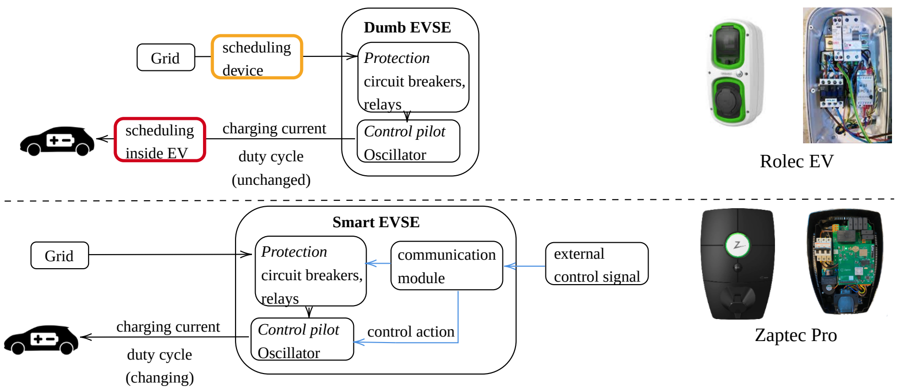


Figure 2.3: Smart EVSE and dumb EVSE comparison.

A *smart EVSE* contains a communication module and can control the control pilot duty cycle, thus modulating or scheduling the charging process. Scheduling refers to turning on-off the charging process. Modulating refers to controlling the charging current through the control pilot. An optional action of smart EVSEs is the ability to control the open-closure of the relays, which allows a three-phase capable EV to perform a switch from three-to-one phase charging, hence, curtailing two of the phases. Here, it should be underlined that those EVSEs which can control their relays also offer the 0 Amp current option. This means that they can keep the EV on-board charger awake without drawing any current for the charging process.

2.1.3 EVSE control architectures

The control approaches of smart EVSE can be divided into centralized, decentralized, and distributed. Table 2.2 merges the findings regarding advantages and drawbacks of each control approach [26]–[28]. So far, smart EVSEs have followed in a large majority the centralized control approach, mainly due to simplicity of implementation and a more mature architecture. Despite that, recent initiatives are exploiting the distributed control approach [29], [30]. The main difference is the location of the intelligence. In the centralized case, the intelligence resides on the cloud, while in the distributed one, it is spread between the cloud and the virtual aggregator (local intelligence). In terms of communication protocol, the difference between centralized and decentralized control is the two-way (server-clients) versus one-way communication path. The centralized architecture has a heavy operation in terms of communication and computation when it is scaled-up. On the contrary, the decentralized architecture requires less communication and computation capabilities [31], [32] and diverts data privacy challenges.

Table 2.2: Advantages and drawbacks of EV chargers control approaches.

Control approach	Advantages	Drawbacks
Centralized	Mature architecture. System wide observation. Easier implementations of optimization algorithms.	Vulnerable to cloud aggregator malfunction being spread on all chargers. Need of a backup server system. Heavy communication and computation when scaled-up. Subject to cyber-attacks and possible data privacy violation.
Decentralized	Diverts data privacy challenges. Low communications and computation capabilities when scaled-up. Low sensitivity to errors and cyber-attacks, thus high system robustness. High deployment scalability. Low communication delays.	Lack of grid observability. Immature control architecture. Risk of avalanche effects. Difficult to reach optimal solutions from optimization algorithms.
Distributed	High scalability and autonomy. System wide observation. Low sensitivity to errors, thus high system robustness. Diverts data privacy challenges. Possibility of plug and play protocols. Low communication delays.	Novel control architecture, thus not mature. Prone to cyber-attacks. High complexity on charger design.

2.1.4 EVSE novel distributed control architecture

Paper [**P2**] introduced a novel distributed autonomous coordination and control architecture. Distributed control combines the benefits of centralized and decentralized control. It grows from decentralized control and tackles decentralized lack of visibility and control algorithms integration by introducing a vertical connection with the cloud aggregator.

To achieve the desired control for the EVSE, two designs were considered: (i) first, a virtual aggregator (VA) and a dumb EVSE device separated, where a single VA can control multiple dumb EVSEs; (ii) second, VA is included in each EVSE, making it a single device. The most important aspect of the EVSE and VA operation is their ability to run autonomously to the largest possible extent. Since the first design is vulnerable of the VA being compromised and losing control of a set of chargers, the second design moved forward. To tackle the above-mentioned shortcomings of the first charger design, the second design has three pieces:

1. Measurement component: the local grid parameters.
2. Virtual aggregator component: the charger intelligence.
3. Charging component: the protection and charging port.

Moreover, Zone D (Fig. 2.4) is the typical representation of the coupling of the consumer or prosumer with the EV charging needs and utility signals. Figure 2.4 shows the power flow and the information path for the charging operation.

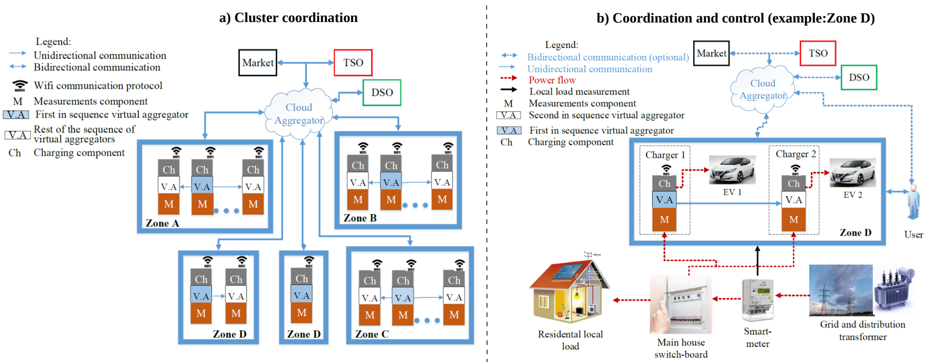


Figure 2.4: a) Visualization of clustering method and communication paths. b) Autonomous EVSE control architecture for zone D.

The first VA takes care of running the operation in the zone and broadcasts its signal to the nearby VA. The EVSE takes input signals from the user, the smart-meter and the cloud aggregator. Based these inputs, the EVSE decides on the charging current for the EV. Depending on the needs and user decision, the charging operation can focus on self-efficiency, time of use tariffs, and better utilization of distributed energy resources (DERs), like rooftop photovoltaic (PV) panels. Furthermore, through the cloud aggregator the charging operation can be part of a larger picture, coordinated by utility, system operator, or market needs.

By applying the simulation model and the use cases presented in **Paper [P2]**, the results displayed the quality of the control by evaluating the priority, speed, overshoot margin of the controller and how it can follow the local PV generation. The overall system delays, the lack of measurement visibility and speed of the controller cannot prevent charging demand to overshoot the reference setpoint.

2.2 EVSE state-of-the-art

Smart EVSE technology is crucial to scaling up the charging infrastructure. Based on the findings of **Paper [P1]**, this section will provide an overview of the current state-of-the-art EVSE technology up to 50 kW, based on 27 different EVSEs which have controllable features. Smart EVSE characteristics are divided into user interaction, charging status information displayed in the physical device, charging and construction data, communication protocols, incorporated smart features, and flexibility features.

Regarding user interaction, the majority of smart EVSEs are RFID (26/27 that means 26 out of 27) and mobile application (27/27) friendly, while physical key (9/27) or pin code (5/27) are less spread. Similarly, LED lights that display the charging status are more often adopted (25/27) compared to physical displays (11/27). From this observation it seems that the future trend for user's interaction with smart EVSEs will be RFID and mobile applications, while for physical charging status, it will be LEDs.

Each single-phase EVSE has a three-phase twin. Currently, the 22 kW charging power dominates over the 11 kW option (21 options for 22 kW towards 8 options for 11 kW). Although most of the EVSEs found are AC EVSE (22/27), few DC chargers examples are also given (5/27).

Regarding the construction of physical EVSEs, charger manufactures are currently competing to make the EVSEs as light and as small as possible. Although the lightest AC EVSE is 1 kg, the DC one is minimum 47 kg. The minimum observed enclosure rating standard is IP54 and in six other EVSE alternatives, an improved standard is followed (four options stick to IP55 and two options keep IP65). Further, 3 out of 27 EVSEs include cooling options, while all EVSEs embody DC current leakage protection and third category surge protection.

According to the description of Open Charge Alliance, open charge point protocol (OCPP) is an open protocol that allows charging point operator (CPO) to control the smart EVSE. Here, the smart EVSEs observed tend to converge to the OCPP 1.6 protocol that allows smart charging features [33]. However, to be future proof, some manufacturers have or are ready to implement OCPP 2.0, since the protocol was made available in April 2018. The OCPP 2.0 is designed to be flexibility friendly [34] and it offers improved functionalities such as device management, transaction handling, security, smart charging functionalities, ISO 15118 support, display, and messaging support. Furthermore, five options are observed to be used to communicate and integrate with external devices, namely 4G (24/27), WiFi (22/27), Ethernet (20/27), Bluetooth (11/27) and RS485 (10/27). The last two are range-limited alternatives.

Furthermore, the smart features attempt to distinguish the inputs that each EVSE can receive and use in a decision-making process. First, the power set point (27/27) is a user or CPO reference input to follow. Second, the smart EVSE can receive consumption measurements from the energy meter (16/27), or otherwise, the EVSE has its own meter that closes the control loop. The home area network (HAN) protocol allows smart EVSE to become part of a larger smart infrastructure. Most (17/27) of the EVSES are HAN friendly, which means they can communicate with other smart home devices. In addition, smart charging options can be provided, such as price-based charging (21/27) or power sharing between devices or using local generation (14/27).

Lastly, flexibility features of the EVSEs are also provided to recognize the flexibility capability that each of the smart EVSEs offers. The scheduling feature is the minimum feature for which an EVSE should be called a smart EVSE. In addition, 24 out of 27 EVSE can modulate the charging current, while only three out of 27 can make the three-to-one phase charging switch.

In conclusion, *a smart EVSE is an electric device providing protection, communication, at least scheduling and at most modulation, phase curtailment (3 to 1-phase switch) and phase switching for the EV charging process.*

A summary of such a definition is provided in Fig.2.5 a). In addition, Fig.2.5 b) presents how the Tesla charger reacts to the nominal three-phase 16 A charging and how modulation occurs to lower the charging current. Additionally, Fig.2.5 c) demonstrates the ability to switch the 16 A three-phase charging of the Tesla Model 3 to a single phase 32 A. When the Tesla charging is switched from the 3-to-1 phase, one can notice that OBC can deliver up to 32 A compared to 16 A. This feature is investigated for different brands in chapter 3. Furthermore, Fig.2.5 c) reveals a state-of-the-art attribute of the Zaptec Pro, the ability to rotate the charging phases, which can be used to optimize the smart charging process and mitigate phase imbalances. Finally, such control features are the backbone of introducing and integrating smart charging strategies and providing grid services (flexibility) from the demand side to the power system.

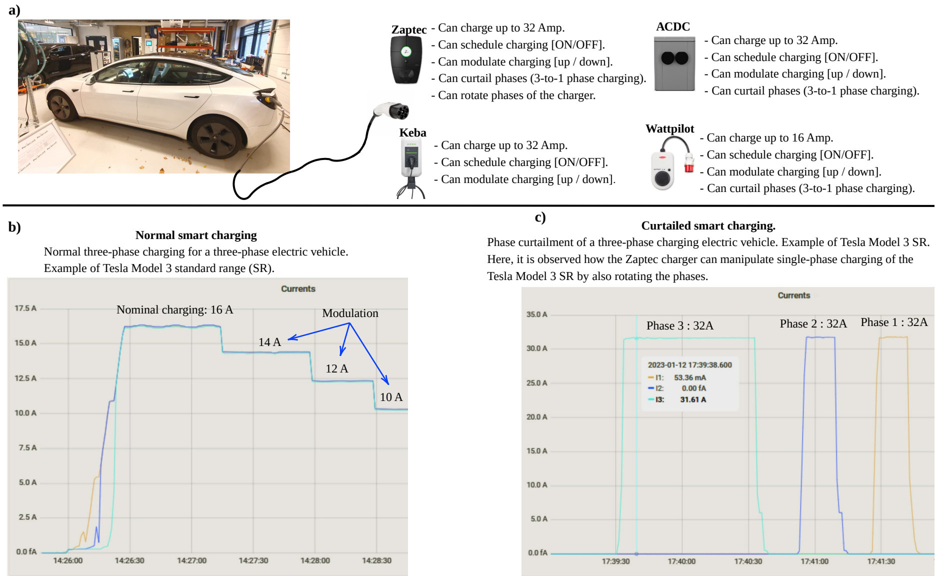


Figure 2.5: a) State-of-the-art of smart EVSEs and corresponding characteristics. Screenshots of the Grafana measurement interface of the DEIF multimeter during b) three-phase charging and c) curtailed charging of the Tesla Model 3 SR.

2.3 Ancillary services and electric vehicle integration

Paper [P1] provides a comprehensive review on ancillary services. All the services required from the perspective of the power system fall under ancillary services [35]. These accounts for all the services offered in the balancing and flexibility markets. Frequency services maintain the system-wide frequency characteristic, while the flexibility services assist local challenges. While for frequency services there is an available market framework, the flexibility services are lacking, or rather we are currently in the first steps of the implementation of such markets. The literature agrees on the allocation of flexibility services based on five features: resource type, duration, incentives, location, and enablers. Therefore, the authors propose the following definition for flexibility services:

Flexibility service refers to scheduling and/or modulation of the collective/single consumption or generation of electrical appliances or distributed technologies, in agreement with the customer (consumer or generator) or mandated in grid code, after responding to signals from market enablers, to increase network reliability and efficiency on a predefined time and location.

2.3.1 Frequency services

The characterization of frequency services according to the type is presented in Table 2.3. Frequency services are divided into activation periods and service types. The periods are the arresting, rebound, and recovery period [36], while the types are I (un-sustained), II (sustained), and III (sustained) [37], [38].

Table 2.3: Frequency services classification. * marks services that can be delivered from EVs via **uni/bi-directional smart chargers (V1G and V2G)**, or only *bidirectional chargers (V2G).*

Type	Explanation	Design stage
Type I: un-sustained *Arrest period* *RoCoF-based activation*	Goal: Should reduce the rate of change of frequency (RoCoF) (prevent triggering RoCoF relays) and delay the frequency nadir.	
1. Inertia [39]–[41]	1. Natural feature of rotating generators from which benefits the frequency stability.	1. -
2. Synthetic inertia* [42]–[45]	2. Capability of converters to try reducing RoCoF by injecting power into the system. Also known to be related to grid following converters.	2. Research proven
*3. Virtual inertia** [44], [46]	3. Capability of converters to try reducing or improving RoCoF by injecting power into the system. Also known to be related to grid forming converters.	3. Research proven
4. Inertia floor [41], [42], [47]	4. Requesting rotating inertia to maintain or improve optimal system's inertia, which mitigates frequency excursions.	4. -
Type II: sustained *Arrest-rebound-recovery period* *Frequency-based activation*	Goal: Should arrest the frequency excursion by preventing a critical frequency nadir that can trigger defence schemes.	
5. Fast frequency reserve* [48], [49]	5. Requesting a power injection with a very fast delivery period, typically less than 2 sec, to be maintained for a predefined time span accordingly to the grid-code.	5. Research proven
6. Frequency containment reserve* [50], [51]	6. Requesting a power injection with a fast delivery period, typically less than 15 sec, to be maintained for a predefined time span accordingly to the grid-code.	6. Research proven Commercial proven
Type III: sustained *Recovery period* *Frequency-based activation*	Goal: Should replace the generation loss and restore normal operation.	
7. Frequency restoration reserve* [52], [53]	7. Requesting a power delivery to restore the frequency deviation to the nominal operating point.	7. Research proven Commercial proven
8. Replacement reserve* [54], [55]	8. Requesting a power delivery (generator rescheduling) to fully clear the frequency deviation.	8. Research proven Commercial proven

This characterization per type is based on three reasons: i) the goal of the service (reduce RoCoF, delay and prevent critical frequency nadir, clear frequency deviation), ii) the stretch on the frequency excursion period (arrest, rebound, and recovery period) and iii) the activation topology (RoCoF or frequency-based). The table summarizes the services presenting type and criteria. The table also highlights in bold and * the five services that can be provided by EVs and their unidirectional smart charger (V1G) or vehicle-to-grid (V2G) chargers. Examples of how frequency services can be provided are as follows: i) phase-locked loop (PLL) to measure RoCoF and a proportional-based control deploys synthetic inertia [56], ii) virtual synchronous machine [57], and virtual oscillator control [58] methods to deploy virtual inertia from grid forming inverters [59], iii) droop-based control for deploying fast frequency reserve (FFR), or frequency containment reserve (FCR) [48], and iv) the automatic generation control (AGC) which is a proportional integral-based control for deploying frequency restoration reserve (FRR) or replacement reserve (RR) [53]. Even if all these services have already been validated in research; fast delivery services such as synthetic inertia, virtual inertia, and FFR are not commercially available. The main reason for this is the requirement to deliver such services with response time below 1 sec. Of the rest of commercially proven services, due to economic feasibility, only FCR is applied in the field, i.e., droop-based control in Denmark [48]. FRR and RR have only been applied in pilot projects. The increase penetration of EVs can mature (reduce the cost) the charging technology, and the rising electricity spot-prices could make FRR and RR economically viable very soon.

2.3.2 Flexibility services

Flexibility services are grouped into three categories: natural, scheduled, and conditional. Natural flexibility services refer to actions actively enabled by the system operator (SO) without the need for a procurement process, namely demand response programs, control of network components and grid code requirements. Scheduled services account for measures procured by the SOs to not jeopardize system safety operation or counteract N-1 situations. N-1 situations represent an operational condition where the grid operator has lost one component of the grid, such as a feeder or transformer. Conditional flexibility services are activated to restore system stability or increase power system efficiency. The difference between conditional and scheduled services is the activation type. For conditional services the activation is post-event, whereas for scheduled services it is a pre-event or during event activation. ”Natural” flexibility comes first, it is a tool based on the agreement with the user only, and it potentially reaches the highest number of flexibility providers, along the timeline. If natural flexibility is not enough, ”scheduled” flexibility is used by SO in a dedicated area, with a specific timeline and fewer providers. Similarly, ”conditional” flexibility is the last resource to avoid further escalation of the problem or help the system recover. Five major topics are recognized: congestion management, voltage regulation, power quality, grid stability, and emission (CO2) management. Here, for a more detailed explanation please follow **Paper [P1]**.

Congestion management refers to the measures taken by SO to maintain the desired loading on their network components, such as transformers and electric lines. The reasons for doing so are twofold: i) high overloading of a grid component will instantly damage the component [60] and ii) moderate overloading will produce heat higher than normal from the current flowing through the device. With time, extra heat shortens the lifetime of the device, requiring earlier maintenance [61].

Voltage regulation refers to measures taken from SO to maintain voltage stability and overcome short-circuit scenarios. Here, the paper distinguishes between voltage and reactive power support. In the former, both active and reactive power play a role, while the latter is more related to reactive power support with a focus on weak grids [62]. The cause of voltage instability derives from the fact that the power network is operated close to stability limits and different load characteristics may trigger fluctuations in the voltage profiles [63].

Power quality refers to the measures taken from distribution system operator (DSO) to improve supply quality and reduce grid operational losses. Here, the voltage regulation service is distinguished from the power quality service because it belongs to both DSO and transmission system operator (TSO). In contrast, the latter belongs to the DSO. Besides, voltage regulation itself has become quite important; hence, it deserves to be mentioned separately. Power quality is focused on the fast dynamics of switching of electronic devices [64], the mitigation of DERs, power flickers [65], [66], and the control of the end-user power factor [67].

Grid stability services cover the power system stability, adequacy, and security of supply outside of the wholesale electricity and balancing markets and are operated by DSO and TSO. Services such as low-voltage/fault ride through, power factor control and anti-islanding are generally capabilities mandated in the grid code. In a high integration scenario of RESs, RESs power smoothing services might be required to operate the system safely and preserve frequency power reserves [65]. Similarly, energy arbitrage and seasonal balancing are believed to be necessary services to cope with the unpredictability of RESs [68], [69]. In addition, emergency power and black-start capability are programmed for blackouts (according to ENTSO-E) [70], or to provide emergency power to areas affected by local emergencies [71].

As the name suggests, *emission management* relates to a demand response service type of use (TyoU) that intends to avoid RESs spilling and reduce consumption from polluting generators. The TyoU induces fees for the carbon intensity depending on the generation mix. Higher fees correlate with high-polluting generators.

Flexibility services are provided in the active and reactive power domains. Recognizing the recommendations of [72] and the novel applications of commercial flexibility [73], [74], stakeholders are only looking at active power services, mainly congestion management. However, recent findings in the reactive power domain suggest a growing need for voltage regulation in low-voltage grid. In the short term, possible commercial flexibility services are demand response programs, TyoU, valley filling, and peak shaving actions. In the long run, with high penetrations of EVs, other flexibility services such as phase balancing, power matching, and voltage regulation actions could be required.

2.4 Charging clusters and flexibility framework

As presented in **Paper [P1]**, an important step before matching the grid services with e-mobility is clustering the EV owners based on their charging behavior. The results can be biased towards early movers [75] as the industry is still in the early stages. However, the literature offers a complete picture of the current available charging data sets in [76], while for charging behavior [77]–[79] are recommended, and for infrastructure deployment[80]–[82] should be considered.

2.4.1 Charging clusters

The scientific literature distinguishes between ”destination charging” and ”charging destination”. In the first, charging is complementary to other user needs, such as going to the supermarket, while in the second, charging drives the choice of user needs. Furthermore, charging behaviors are reflected at different charging sites: i) home and public residential charging; ii) curbside and semi-public charging; iii) workplace charging; iv) fleet charging; v) large semi-public charging; vi) fast (en route) charging; vii) special semi-public charging; viii) charging forecourts; ix) semi-private charging and x) charging hubs. Although it is still quite early for the clusters to mature, the charging clusters derived from the review are in line with the clusters used in Working Group 4 of the IEA GEF Global e-mobility program.

Consequently, Figure 2.6 illustrates with examples the charging site operator (CSO), which is the representative of the cluster. The CSO can incorporate one charger, in the case of a home charger, or include multiple chargers, such as the charging forecourts. The higher the site hierarchy, the fewer chargers there are, while the site connection capacity increases. Furthermore, it is a challenging task to estimate the number of chargers in each cluster. This factor is one of the current limitations on forecasting flexibility of charging clusters. In addition, the charging technology needs to be mature before trying any estimation. For example, most slow chargers today are single outlet; however,in order to increase utilization efficiency, dual outlet options are investigated.

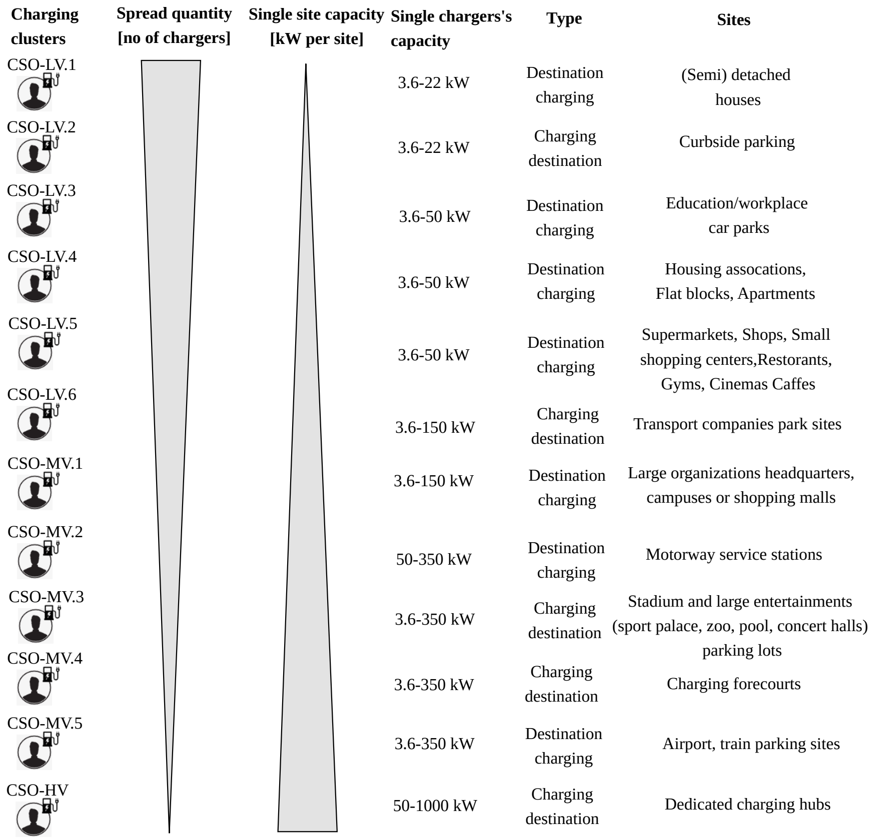


Figure 2.6: EV charging clusters.

2.4.2 E-mobility flexibility map

After identifying the charging clusters or CSOs, Figure 2.7 matches the charging clusters with their grid location (low/medium/high voltage). Besides, it couples CSOs with possible delivery of flexibility and frequency services. This is achieved by matching the previously discussed ancillary services depending on

V1G or V2G. The V1G represents a smart load, while V2G (converter technology) is similar to battery energy storage. Furthermore, the drawing in Figure 2.7 pairs each CSOs with the charging technology (AC and DC smart chargers) and with different EVs ownership types (passenger cars, taxis and fleets, autonomous vehicles, shuttles, and public transport buses).

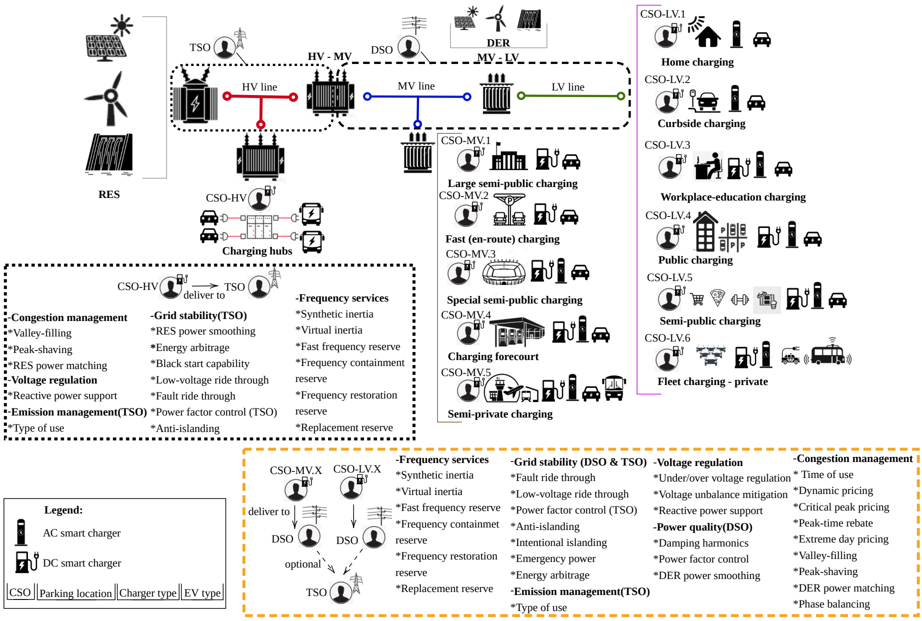


Figure 2.7: E-mobility flexibility map.

Overall, five out of eight frequency services and 26 out of 32 flexibility services can be provided by EVs. However, in three out of eight frequency services only, the charging technology is on a commercial stage. Similarly to what happens for flexibility services, congestion management services are mostly being developed for commercial applications.

2.4.3 Flexibility framework

Figure 2.8 a) displays the flexibility architecture with all stakeholders, namely the EV-user, the CSO, the CPO, the aggregator, the energy community, the DSO, the TSO, and the flexibility platform. The EV-user provides consent of using its flexibility to the CSO [83]. The CSO is the first flexibility provider. Furthermore, the CSOs require an infrastructure to operate, namely the EV charger. The CSOs are supplied from charger manufacturers and can operate the infrastructure on their own or delegate it to someone else. Here, the CPOs concept is introduced, which can control (back-end control) the charging infrastructure.

A CPO can interface with one or multiple CSOs accordingly to the CSO desires. On the one hand, the CPO can deliver bilateral flexibility service to the SO. On the other hand, CPO can delegate front-end control (API interface) to an aggregator [84] or an energy community to participate in the flexibility market. In this case, a larger entity is created, and CPO can help the process by providing flexibility forecasts of their sites to the aggregator or energy communities.

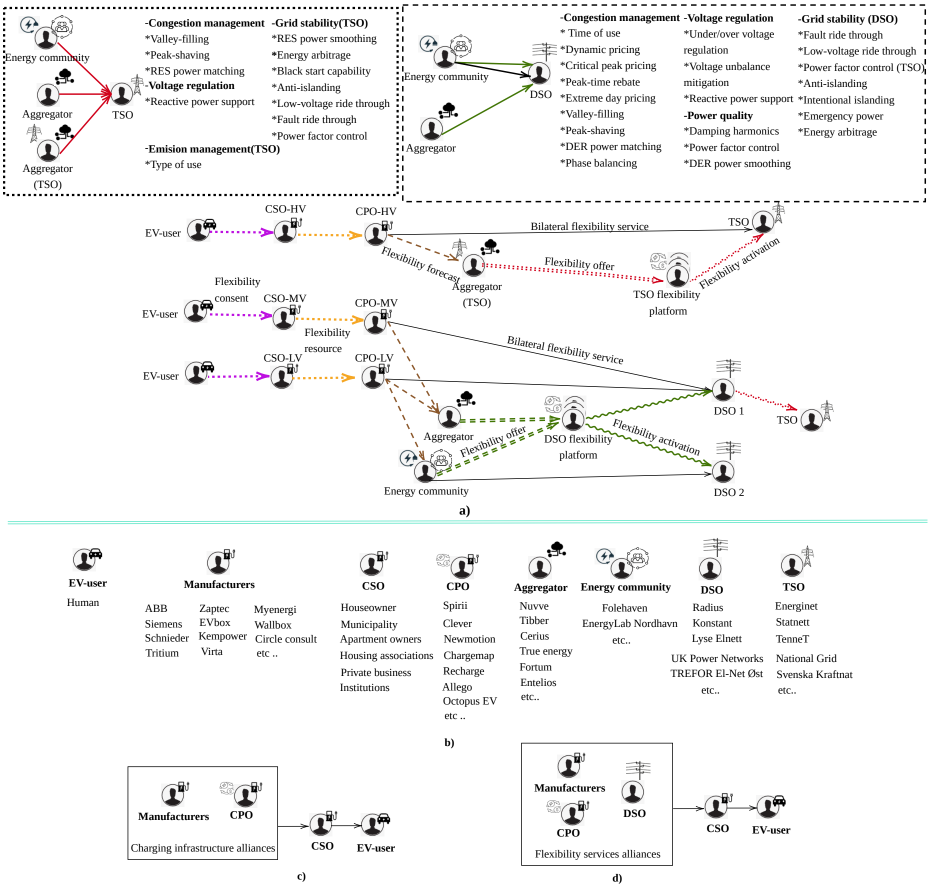


Figure 2.8: a) Flexibility services architecture. b) The EVs flexibility supply chain. c) Charging infrastructure alliances. d) Flexibility services alliances. Examples are provided for the Nordic countries cases.

Subsequently, the aggregator or energy communities bid a flexibility offer in the flexibility platform related to the DSOs or TSO network. The platform decides the winning bids and activates the flexibility service. Consequently, in Fig. 2.8 a) a summary of the flexibility services from the aggregating entity is presented. Furthermore, Fig. 2.8 b) illustrates the supply chain of flexibility services provided by EVs, including examples from the Nordic countries. In addition, one can distinguish the actors in e-mobility domain. Finally, in Figs. 2.8 c) and d) it is displayed recent examples of alliances to bypas regulatory and technical challenges. A typical example is Powerloop, a project implemented in the United Kingdom between Wallbox, Octopus EV, and UK Power Networks. Similarly, the FUSE research project aims to combine Zaptec, Spirii, and Radius to simplify the development of flexibility services. Zaptec supplies a state-of-the-art V1G to Spirii, which is the CPO. Spirii offers to its customers the possibility to participate in congestion management services. Radius, a Danish DSO will utilize the Spirii infrastructure to their benefits. Additionally, a more ambitious aggregator and CPO-free path is followed from the ACDC project.

2.4.4 Barriers and solutions

Alliances have recently been observed between CPOs and charger manufacturers. On the one hand, these alliances are made to offer a complete charging infrastructure package to end users and CSOs. On the other hand, to participate in electricity markets, an entity must become a balancing responsible party (BRP) and fulfil size, market, and grid requirements. Barriers such as size and market requirements can be overcome by forming alliances between SOs, and CPOs. Thus, different stakeholders are bypassing these barriers by offering a full charging service package that includes charging infrastructure and smart charging incentives.

Paper [P3] further discusses the technological and regulatory barriers for the integration of EVs in the power grid. In addition to EVSE technology and control methodologies, grid observability and smart metering are two other challenges. In most countries where smart meters are in use, the DSO takes charge of certifying and installing all units, along with the responsibility for data collection and administration. It is crucial in this context to precisely delineate the prerequisites for distinct measurement parameters, including factors such as sampling rate. This choice requires a careful balance between the speed of data acquisition and the cost associated with installation and data management.

The European Clean Energy Act requires that smart meter functionalities must include remote reading with two-way communication and a sampling rate not greater than 15-min [85]. However, there are no international standards that would ensure these functionalities, so the status across Europe varies considerably. The rollout of smart meters should be coupled with information and communication technology (ICT) that ensure advanced metering, control, and transactional communication among different stakeholders.

In addition, the economic framework for flexibility services is a central barrier that hinders the development of a flexibility value chain. The DSOs followed a straightforward approach to address grid congestion and voltage concerns, focusing primarily on reinforcing the grid infrastructure as necessary, a strategy often referred to as the ”fit-and-forget” approach. The economic and regulatory structures were consequently designed around this paradigm, with DSOs being compensated based on the capital expenditures (CAPEX) associated with grid upgrades. However, the transition towards smarter grid solutions necessitates a fundamental shift towards a comprehensive expenditure framework, often referred to as TOTEX (total expenditure). Under this model, DSOs are required to minimize not only their CAPEX but also their operational expenditures (OPEX). Currently, this transition is only partially realized, and there remains a need for regulatory reforms that incentivize DSOs to proactively manage their expenditures and harness the potential of load flexibility more effectively.

Lastly, DSOs can employ various approaches to offer flexibility, with distinctions between grid code-based, contract-based, and market-based strategies. The grid code-based approach requires that DSOs establish direct requirements for flexibility provisioning or enter into contractual agreements directly with EV users, allowing them direct control over the EV charging process. On the contrary, market-based approaches introduce an additional layer of interaction between DSOs and TSOs. To facilitate communication between DSOs and EV users, the involvement of aggregators is often required. These aggregators can group multiple EVs and efficiently manage their flexibility, transforming them into tradeable service packages.

The interaction between DSOs and TSOs is increasingly recognized as a critical aspect, particularly within the framework of the European Clean Energy Package, as the integration of RES and DER continues to grow. This importance arises from the fact that distribution and transmission networks often exhibit distinct and, at times, conflicting requirements.

Finally, Table 2.4 summarizes the recommendations to overcome the technical, economic, and regulatory barriers. From a technical perspective, the primary constraint hindering the widespread adoption of smart charging pertains to ICT. It is essential to advance existing standards and protocols to ensure seamless interoperability between EVSEs and EVs, enable user-EVSEinteraction, and enhance grid observability. Economically, two key focal points emerge. The first centers on the development of market platforms that facilitate the trade of services. The second refers to the design of business models that ensure profitability for investors in EV infrastructure, aggregators, and prosumers.

Table 2.4: Future steps for the advancement of resilient EV infrastructure for distribution grid services in each of the examined domains.

Technical framework	Economic framework	Regulatory framework
Advance research and development in smart charging capabilities.	Keep or introduce temporary incentives for cars, shared mobility and mobility-as-service.	Enhance active management requirement to DSOs.
Standardize and ensure interoperability between different EVs and EVSE.	Research on business models for aggregators and charge point operators.	Standardize cost-benefit analysis for smart meters.
Develop and harmonize charging standards (especially V2G).	Develop new network tariff structures.	Ensure a clear classification and standardization of V2G connection requirements for V2G prosumers.
Improve user engagement and interconnectivity.	Position various charger types strategically to instill confidence in investors.	Create incentives for smart chargers purchase.
Continue the demonstration project campaigns to gather data.	Establish local flexibility platforms with increasingly competitive approaches.	Define DSO-TSO priorities and the interaction between every stakeholder.
Increase grid observability.	Revise and improve the economic framework of flexibility from the lessons learned.	Set ambitious targets (CO2 reduction, targets for different transport types).

In conclusion, the regulatory framework must set ambitious objectives and incentivize both the technical and economic grown the growth of the EV value chain. This can be achieved through the standardization and incorporation of various technologies in the value chain, the definition of their available products, and the regulation of interactions among relevant stakeholders.

CHAPTER 3

Smart charging from theory to practice

3.1 Onboard chargers and efficiency of AC smart charging

Recalling from chapter 1, when an EV is connected to an AC charging station, the OBC within the vehicle converts the incoming AC power to DC to recharge the battery. The EVSE is responsible for communicating, via the charging cable, the maximum charge current allowed to the vehicle. However, it is the EV BMS that controls the OBC operation and decides the final charging current according to the needs of the battery pack.

3.1.1 Onboard chargers

There are two types (dedicated and integrated) of OBCs. Figure 3.1 provides a detailed visualization of the OBC technologies. The most common OBC technology is shown in Fig. 3.1 a). The input AC supply and the DC output to the high-voltage battery pack can be seen. In addition, there is a DC low-voltage output for the vehicle's auxiliaries. The latest generations of OBCs even incorporate liquid cooling for better heat anticipation and increased charging efficiency. Lastly, the OBC communicates via CANBUS with the vehicle's electronic control unit. As mentioned in Chapter 1, the dedicated OBC technology is market-dominant compared to the integrated one. Moreover, for the dedicated OBC technology, Fig. 3.1 b) presents a unique type employed by Tesla. The dedicated Tesla OBC utilizes the same unit for AC and DC charging. Tesla has reduced the need for extra input and output DC cables by combining them with AC cables and having only one DC output that supplies the high-voltage battery pack.

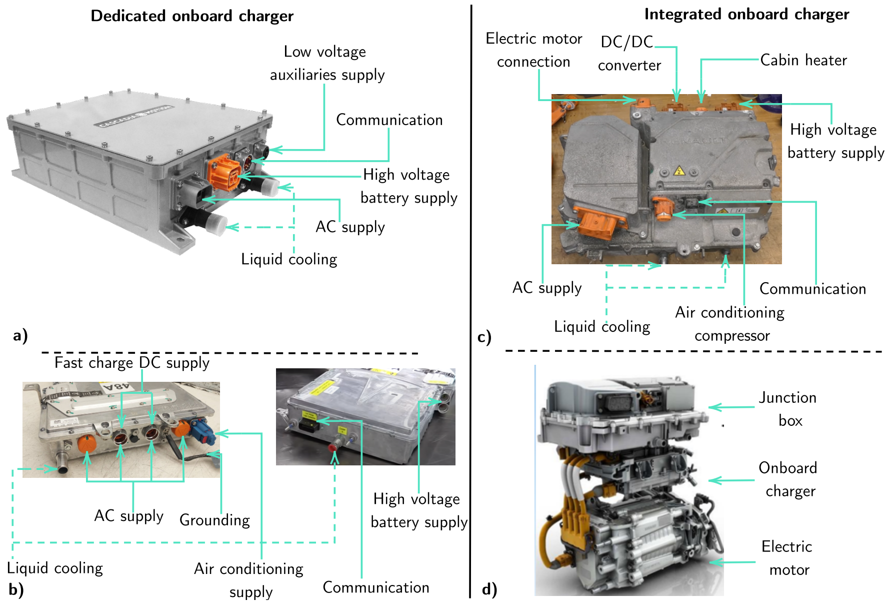


Figure 3.1: Overview of different onboard charging technologies. a) Cascada Motion 6.6 kW OBC. b) Tesla Model S/X 48A OBC. c) Renault Zoe Chameleon 43 kW OBC. d) Complete view of Renault Zoe 43 kW Chameleon's integrated OBC.

Furthermore, Fig. 3.1 c) provides an overview of the integrated OBC technology, more specifically the Renault Zoe Chameleon 43 kW. Such a system does not require additional power electronic components; instead, it uses the electric motor windings as an inductor. Figure 3.1 d) explains how the integrated OBC fits into the Renault Zoe. The junction box is required to combine different OBC outputs with their respective destinations. Subsequently, due to the importance of OBC in charging operation, it is important to investigate electrical characteristics such as efficiency and reactive power consumption.

3.1.2 Onboard charger efficiency and reactive power draw

A review of the literature highlights the lack of tested AC-to-DC conversion efficiency values for EV OBCs [86], albeit the most energy-intensive load in the household. Such conversion efficiency values from AC to DC are critical for the optimal large and small-scale management of charging strategies [87] for EVs, life cycle assessment [88] and understanding the global energy implications of charging demand [89]. The knowledge gap for OBC efficiency is even acknowledged by the European Commission in the European efficiency labeling regulation [90], [91]. The European efficiency label has been successful in helping consumers make better decisions and reducing European energy needs. Thus, **Paper [P4]** delves into measuring the OBC electrical characteristics, such as efficiency, reactive power, and power factor (PF).

The study covers the average values obtained from vehicle tests conducted in a controlled temperature environment. Each vehicle underwent four test cycles: two test cycles with a state-of-charge (SOC) lower than 50% and two cycles with a SOC greater than 50%. Before highlighting the key findings, it is essential to acknowledge the range of measurement error. The efficiency, which denotes the AC-to-DC conversion efficiency, is subject to an uncertainty of 2-3% at 6 A and decreases linearly to 0.2-0.5% at 32 A. Nevertheless, it should be noted that the loss-to-charging current ratio is more pronounced at lower charging currents and significantly lower at higher charging currents. Additionally, the accuracy of the reactive and apparent power measurements is based on the quality of the DEIF multimeter, rated ts class 0.1.

Figure 3.2 illustrates the results in the form of parabolic efficiency during standard smart charging for three-phase vehicles. This parabolic observation aligns with our earlier explanation regarding the losses-to-charging current ratio in different current ranges. The results also indicate a consistent improvement in efficiency from 2011 to 2022 at all charging current values.

Furthermore, the PF, which denotes the ratio of active power to apparent power, serves as a key indicator of the efficiency of the utilization of electrical power. A PF of 1 signifies the optimal utilization of the power supplied for productive work, while a PF of less than 1 suggests a waste of power. The PF values, as depicted in the PF heat map in Fig. 3.2, are limited within the range of 0.9 to 1, according to the requirements of the EU Commission Regulation 2016/1388 for connection of low-voltage grid demand [92]. Notably, newer models exhibit improved PF values, with most approaching unity PF.

The finding illustrated in Fig. 3.2 suggests a correlation between lower PF values and higher reactive power consumption. During low-current charging, some models violate the regulations pertaining to low-voltage grid demand connection, and several models exhibit substantial reactive power consumption. Consequently, there is a pressing need to reconsider the regulations concerning such high levels of reactive power consumption, as it poses a potential threat to the integrity of the low-voltage grid. Additionally, the data concerning reactive power reveal six distinct clusters of reactive power consumption curves. Clusters 1-5 represent behaviors of dedicated OBC, which is the majority of the automotive industry. Most of EVs, spanning from early to the most recent models, consume reactive power within the range of 200-700 VAr, following a similar pattern to the Polestar 2 Long Range Dual-Motor (LRDM) (cluster 1). In general, the cluster's reactive power consumption diminishes as the charging current increases.

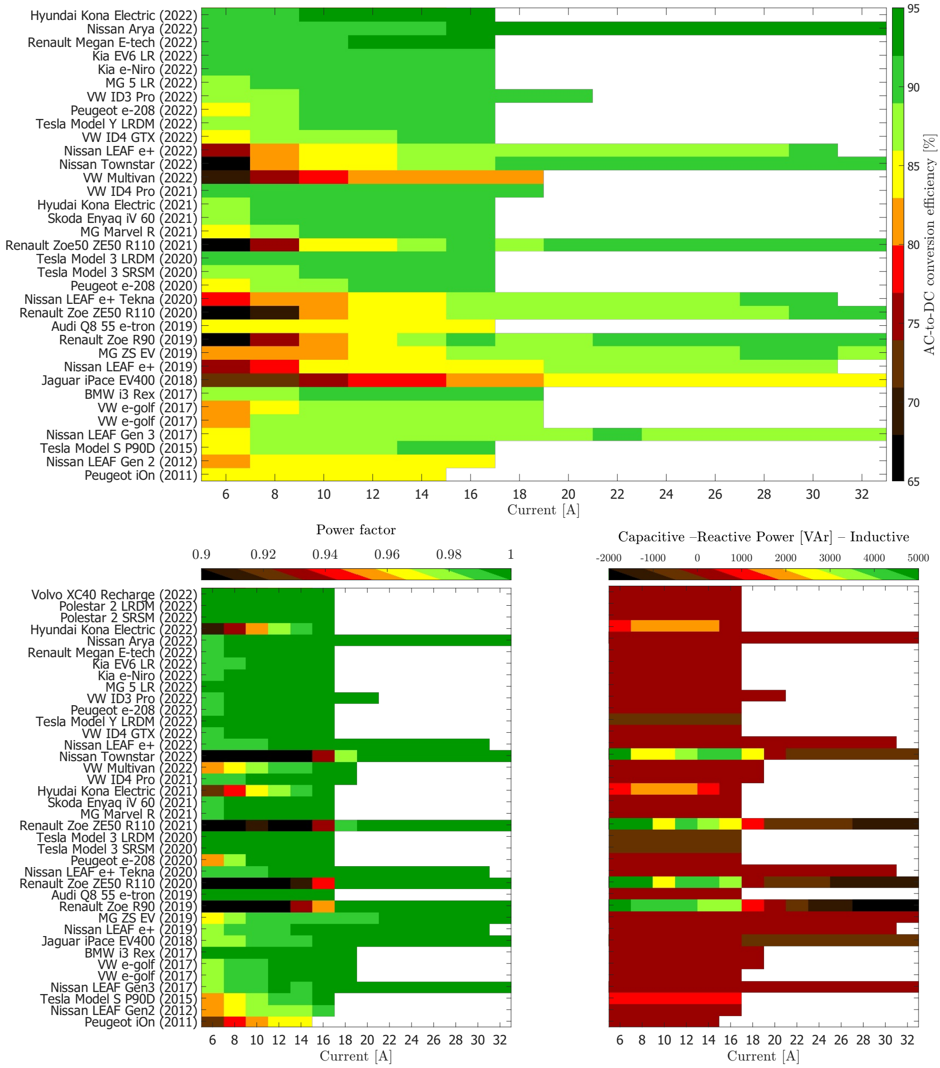


Figure 3.2: EV OBC characteristics. Top) AC-to-DC conversion efficiency. Bottom left) PF. Bottom right) Reactive power consumption from 2011 to 2022.

In contrast, the Tesla Model S P90D (400 V battery architecture) and the Kia EV6 LR (800 V battery architecture) represent the typical charging behavior of clusters 2 and 3, respectively, showcasing an increasing trend in reactive power consumption as the charging current increases. Consequently, this behavior cannot be solely attributed to a specific battery voltage architecture (400 or 800 V), as it can be found in both architectures. Hyundai Kona represents cluster 4, characterized by an almost complete parabolic pattern of charging behavior. Within this cluster, the highest levels of reactive power consumption occur in the mid-range of charging current (between 10-12 A). In contrast, Tesla Models 3/Y represent the charging behavior of cluster 5, showing a negligible reactive power consumption (around 0 VAr). Lastly, cluster 6 encompasses EVs with an atypical level of reactive power consumption which employ a similar OBC as the Renault Chameleon/Zoe (integrated OBC with the electric motor).

3.2 Optimizing smart charging

Understanding the charging efficiency of the OBC facilitates the optimal implementation of smart charging strategies. Subsequently, the optimization parameters discussed in this manuscript take into account smart charging efficiency. In light of recent discoveries, **Paper [P5]**, it is necessary to explain the efficiency gains or drawbacks from normal or curtailed smart charging.

3.2.1 Curtailed charging

Paper [P5] presented the characteristic of curtailing two phases from three-phase charging vehicles. In addition, the three-to-one phase switching can be manually or automatically decided by the operator.

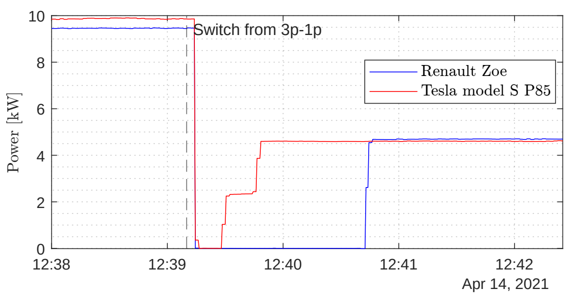


Figure 3.3: Demonstration of three-phase to one-phase charging curtailment with Zaptec Pro chargers.

Figure 3.3 displays both Tesla Model S P85 and Renault Zoe 40 that initially charge with 32 A in three phases. After 15 seconds, the switch to the single-phase command is initiated. During the transition from three-phase to one-phase charging, EVs do not consume power from the grid and are not disconnected from the charging process. The three-to-one phase switching similarly initiates a single-phase charging with 32 A. However, the transition period is different for the tested EVs. Although both EVs react quite similarly to power reduction, there is a significant difference when one-phase charging re-starts. Another important result to mention is that the transition to one-phase charging can only be achieved through the first phase of the EV OBC. The vehicle enters an error state if an attempt is made to charge on a single phase through the second or third phase of the vehicle OBC, as presented in Fig. 3.4. The OBC can charge only with a single phase, by using the first phase, in the case of curtailing a three-phase vehicle.

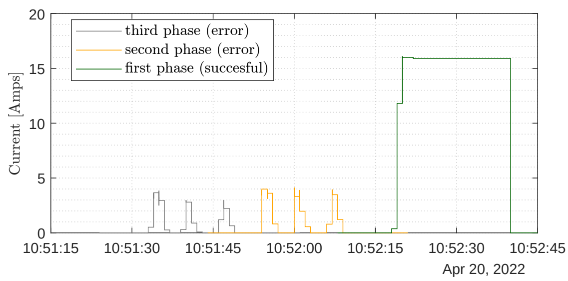


Figure 3.4: Testing the ability to charge on single phase for Renault Zoe 40.

3.2.2 Three-phase versus curtailed charging

The possibility of curtailing three-phase charging opens up the opportunity to better optimize charging operation in parking lots, fleets, or clusters controlled by an aggregator (as presented in **Paper** [**P4**]). Such a strategy has as its objective the fulfilment of the required energy demand (in kWh) without compromising the grid capacity connection (in kW) and the allowed consumption of reactive power (in kVAr). Grid connection capacity is generally the biggest constraint for charge-point operators. Therefore, smart charging is employed to maintain the acquired grid connection capacity from the DSO. However, modulating the charging current has additional implications for the OBC efficiency, as shown in Fig. 3.5.

The OBC efficiency results can be clustered into six patterns.

1. Vehicles that charge with 16 A in three-phase (11.04 kW) and single-phase

(3.68 kW) (cluster representative Skoda Enyaq iV 60). The efficiency of single-phase charging is lower than three-phase charging.

2. Vehicles that charge with 16 A in three-phase (11.04 kW) and single-phase (3.68 kW) (cluster representative Hyundai Kona Electric). The efficiency of single-phase charging above 14 A (3.22 kW) is higher than the efficiency of three-phase charging below 8 A (5.52 kW).

3. Vehicles that charge with 32 A in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Renault Zoe ZE50 R110). The efficiency of single-phase charging greater than 16 A (3.68 kW) is higher than the efficiency of three-phase charging below 12 A (8.28 kW).

4. Vehicles that charge with 16 A in three-phase (11.04 kW) and 32 A in single-phase (7.36 kW) (cluster representative Kia e-Niro). The efficiency of single-phase charging is lower than three-phase charging.

5. Vehicles that charge with 16 A in three-phase (11.04 kW) and 32 A in single-phase (7.36 kW) (cluster representative Peugeot e-208). The efficiency of single-phase charging is sometimes better than that of three-phase charging.

6. Vehicles that charge with 32 A in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Nissan Ariya). The efficiency of single-phase charging is lower than three-phase charging.

Moreover, the viability of curtailed charging should be carefully analyzed by also considering the reactive power consumption. Figures 3.5 a), b) and c) introduce the pattern of reactive power consumption for curtailed charging. Similarly to three-phase charging, there are six typical curves for curtailed charging. However, two patterns behave differently, specifically Hyundai Kona and Renault Zoe. Finally, when curtailed charging is considered, the three-phase reactive power is not equal to that of three single-phase charging. Subsequently, there exist two options:

1. Lower reactive power consumption. For example, Kia EV6 Long Range (LR) consumes 471-606 VAr in three-phase charging. However, it consumes 135-186 VAr in curtailed charging. Therefore, 3 x (135 to 186)[VAr] $<$ (471 to 606)[VAr].

2. Higher reactive power consumption. For example, polestar 2 SRSM consumes 442-183 VAr in three-phase charging. However, it consumes 368-257 VAr in curtailed charging. Therefore, 3 x (368 to 257)[VAr] $>$ (442 to 183)[VAr].

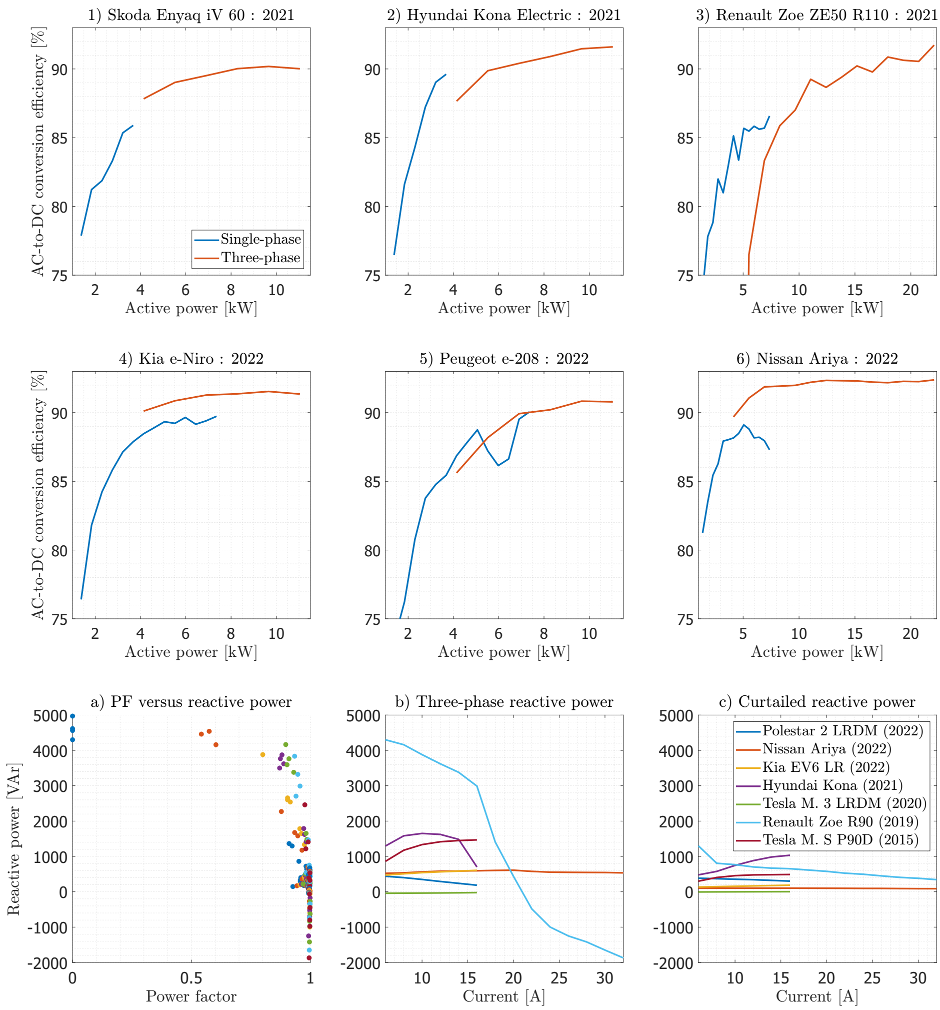


Figure 3.5: Comparison of OBC efficiency between clusters of single-phase curtailed and a three-phase charger (1-6). Depending on which efficiency pattern the vehicle belongs to, the charging process can be optimized by looking at such efficiency curves. The correlation between lower PF and higher reactive power consumption a). Seven patterns of b) three-phase reactive power consumption are experienced similarly during c) curtailed reactive power consumption.

Lastly, when looking for trends in the behavior of the OBC, the vehicle's SOC does not affect the efficiency of the OBC or reactive power consumption.

This result confirms that the SOC only affects the amplitude of the charging current requested by the OBC. For example, a charging current of 10 A has the same efficiency and reactive power consumption at low (i.e. 40%) and high (i.e. 92%) SOC. In summary, the results show that decision-making for efficient smart charging should be made based on the individual vehicle model. CPOs can benefit from curtailed charging by better utilizing the available grid capacity; however, curtailed charging can reduce power quality by increasing reactive power consumption.

3.2.3 Current and future OBC performance conundrum

So far, small- or large-scale energy simulation models do not consider OBC efficiency. The results presented in this manuscript highlight the importance of considering such an approach. Depending on the level of modulation required, smart charging could increase the charging energy demand from 1-10 %. Furthermore, the testing campaign showed that efficiency varies between years and vehicle models. The efficiency curves are suggested to be implemented in large-scale simulations. However, it is acknowledged that such a method can be computationally heavy. Thus, a more generalized approach is proposed in Fig.3.6. On the basis of the test results, a second-order polynomial is fitted for three-phase, curtailed, and single-phase vehicles. Such polynomials can be replicated to calculate the energy efficiency of EVs in an aggregated manner or for large-scale simulations.

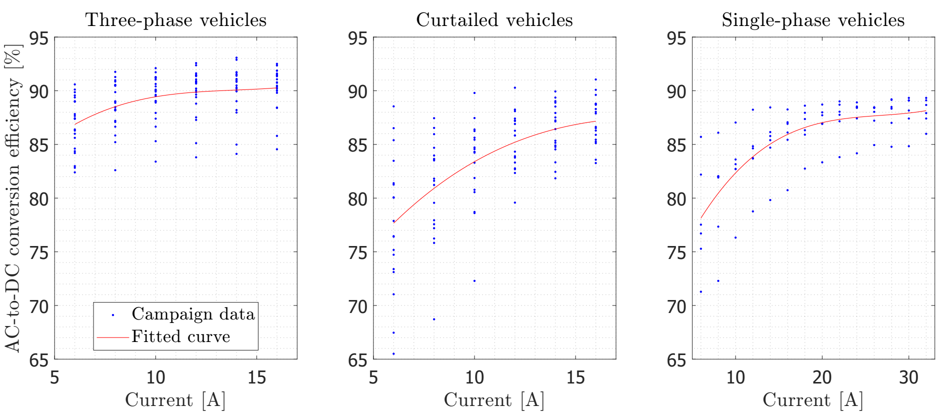


Figure 3.6: Efficiency curves fitted to the data obtained from the testing campaign for left) three-phase, center) curtailed, and right) single-phase vehicles.

In Figs 3.7 a) and b) historical efficiency data are plotted alongside a second-order fitted function. As can be seen, the OBC maximum efficiency has progressed over the years. For 2022 the average efficiency is 90%, while the OBC minimum efficiency lies around 83%. Based on 11 years of data, a second-order polynomial prediction of efficiency is displayed up to 2040. The prediction considers a conservative approach, in which the technology will develop at a faster rate until it saturates at a 96% efficiency value in 2035. These saturation levels for the development of OBC efficiency align with historical developments in solar inverters, which are a good example of technological progress [93]. Therefore, earliest by 2030 it could be possible to reach a maximum OBC efficiency of 95% as a market average product. Similarly, by 2030 it could be possible to support a value of 88% for the minimum efficiency of OBC and a saturation of efficiency of 90% in 2035. The data suggest that the fleet of EVs varies considerably in its efficiency values. This uncertainty complicates the optimization of EVs; therefore, it needs to be addressed with technological improvements.

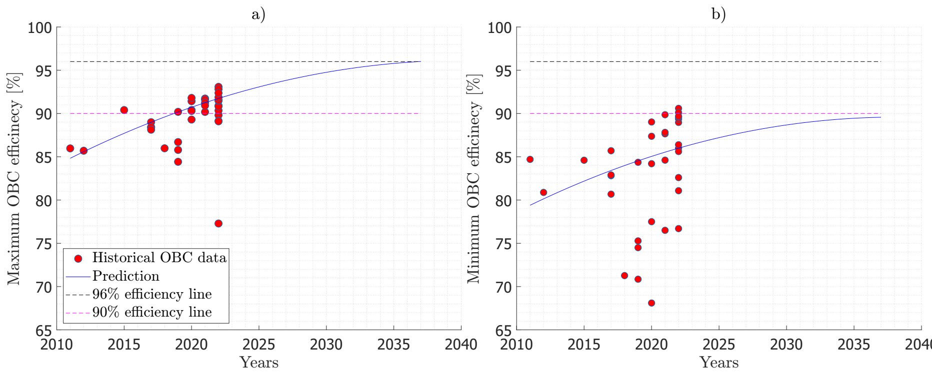


Figure 3.7: Evolution of (a) maximum and (b) minimum OBC AC-to-DC conversion efficiency.

3.3 Control capabilities of EVSEs and electric vehicles

While the previous sections dealt with the charging technology inside the EV, the following section investigates the control capabilities of the EVSE and OBC to provide grid services. The work is based on **Paper [P6]**.

3.3.1 Communication and control framework

To achieve the provision of grid services with EVs in AC charging mode, several steps must be followed. For example, to deliver frequency services to the TSO, the control will involve the aggregator to CPO followed by the EVSE manufacturer cloud to EVSE and the vehicle itself. Subsequently, it is necessary to distinguish two communication paths. On the one hand, there is over-the-air communication between the aggregator-CPO-EVSE. On the other hand, there is physical communication between EVSE-EV.

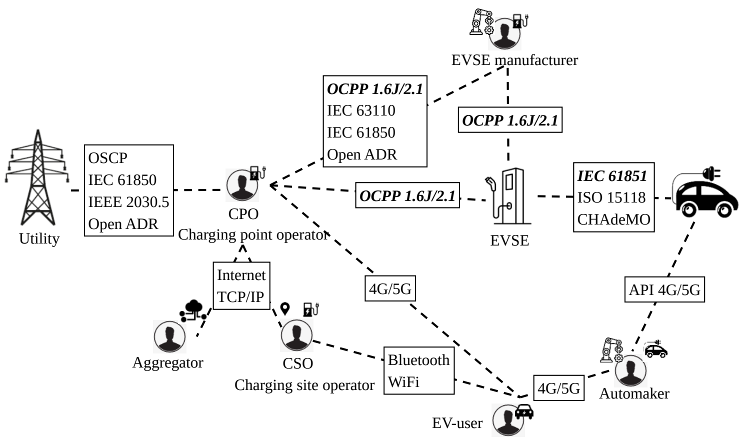


Figure 3.8: Communication standards for delivering grid services.

OCPP stands as the prevalent protocol utilized for over-the-air communication, while IEC 61851 is the standard that defines the communication between EVSE and the OBC of an EV. According to the IEC 61851-1 standard, specific EVSE timings are required, notably t_{external} and t_{ichange}. The former, t_{external}, denoting the maximum allowed response time (10 seconds) for external commands, encompasses manual adjustments or directives from grid management systems to the EVSE. Subsequently, t_{ichange}, capped at 5 seconds, represents the maximum time allocated to the vehicle OBC to modify the charging current following modulation in the pulse width modulation (PWM) duty cycle.

In compliance with the IEC 61851-1 standard, a 15-second window is granted for response to new control set points from the aggregator to the EVSE and EV, encompassing changes in charging configurations. Our investigation introduces the practical measurement of t_{external} and t_{ichange}. While the latter is specific to the vehicle's OBC and potentially diverges among different automakers, t_{external} can face different delays depending on the communication and control approach chosen (distributed, decentralized or centralized).

Figure 3.9 explains the overall differences in the control scheme and visualizes the contributions of **Paper** [**P6**] in terms of understanding the physical t_{external} and t_{ichange} delays. For instance, in delivering frequency services to the TSO, the local control approach theoretically offers a reduced delay compared to the centralized approach. However, the local approach incurs higher costs due to the requisite of multiple local meters in contrast to the centralized approach, which relies on a single measurement point. Moreover, while frequency services are highly demanding on the control timescale (fast phenomenon), other grid services, such as voltage regulation or congestion management, are slower phenomena.

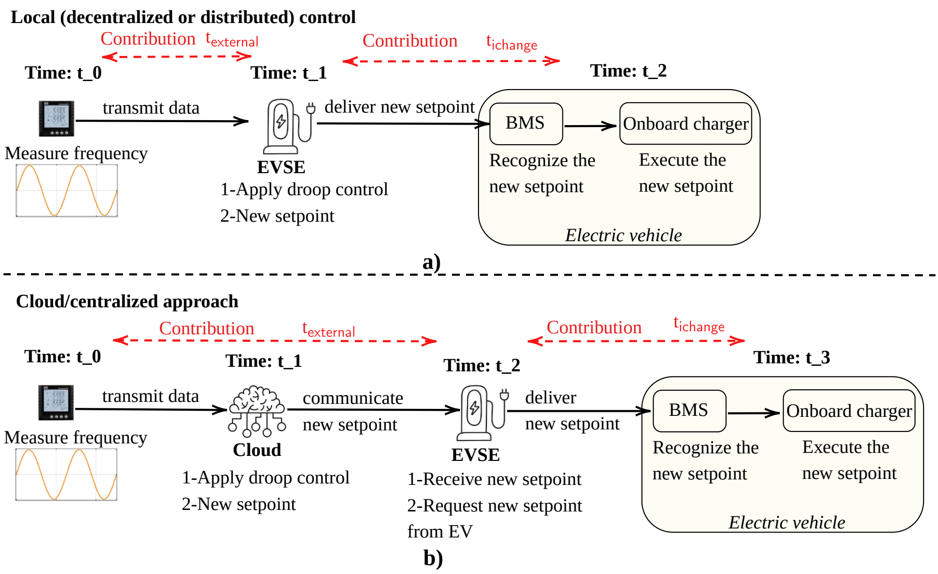


Figure 3.9: Visualization of the delays when offering a grid service (frequency regulation example) with EVs.

3.3.2 EVSE and electric vehicle charging dynamics

The smart EVSE testing sample consists of ACDC, Keba P30, Zaptec Pro, and Wattpilot 22. These EVSEs represent different control approaches as explained below:

- ACDC : The operator communicates directly with the EVSE.

- Keba P30: The operator uses OCPP 1.6J (native OCPP) to communicate with the EVSE.
- Zaptec Pro: The operator utilizes OCPP to connect to the Zaptec backend (virtual OCPP), and the Zaptec server communicates with EVSE.
- Wattpilot 22: The operator communicates locally through WiFi with theEVSE.

Table 3.1 summarizes the results obtained from testing the different EVSEs, by presenting the slowest, minimum, maximum and median of t_{external}. One can observe that Zaptec Pro is faster than other EVSEs. Keba P30, which employs OCPP 1.6J, is the slowest of the tested units. ACDC control topology slightly resembles that of Zaptec, however, it is slower in response time. In addition to the fastest and slowest times in Table 3.1, the median delay is presented. This delay value is more important for properly modeling t_{external}.

Table 3.1: t_{external} for different EVSE brands and control methodologies.

Delay	**ACDC**	**Keba P30**	**Zaptec Pro**	**Wattpilot 22**
Minimum [s]	1.8	15.7	0.55	0.83
Maximum [s]	0.95	10	0.37	0.48
Median [s]	1.6	14	0.4	0.7

3.3.3 Electric vehicle charging dynamics

There is a growing demand to dynamically model the charging behavior of EV. Figure 3.10 provides a detailed visualization of key performance indicators (KPIs) used to measure the charging dynamics of the vehicle OBC. The ramp-up rate, measured in [A/s] or [kW/s], describes the OBC rate limitations for drawing current. The values are measured in A/ms; however, for better understanding, they are converted to A/s. Similarly, the ramp-down rate measures the rate of reduction of the charging current.

Furthermore, t_{a} is the time that vehicle OBC needs to wake up from a non-charging position (0 A). The time required to go from zero to full charging current is t_{b}. The OBC delay to respond to a received command (decrease charging current) during the operation mode is t_{c}. The time needed to go from full charging to the minimum allowed charging current (6 A) is t_{d}. The OBC delay to respond to a received command (increase charge current) during operation mode is t_{e}. The time needed to go from the minimum allowed charging current (6 A) to full charging is t_{f}. Lastly, t_{g} is the time required to go from full charging current to zero. Hence, t_{ichange} should differ during the different charging states as follows:

- Charging start-up or state change from connected (state B) to charging (state C): $t_{\text{ichangestart}} = t_{\text{a}}$
- Charging ramp-down: $t_{\text{ichangerd}} = t_{\text{c}}$
- Charging ramp-up: $t_{\text{ichangerp}} = t_{\text{e}}$
- Charging stop: $t_{\text{ichangestop}} = t_{\text{c}}$

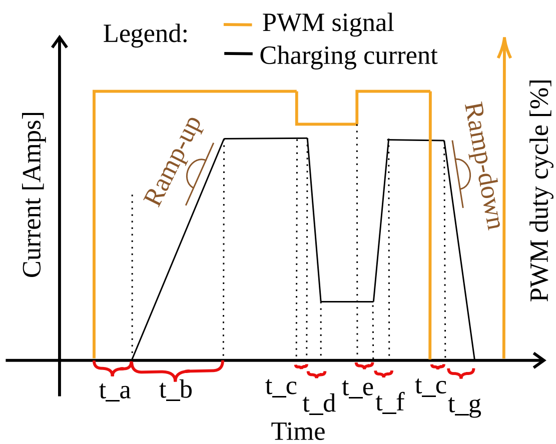


Figure 3.10: Visualization of the KPIs used for the EV charging dynamics.

Table 3.2 summarizes the results of the vehicles tested. As the data confirms, t_{a} exhibits the longest delay and corresponds to the change in the charging states from connected (B) to charging (C). The IEC 61851-1 standard stipulates a maximum reaction time (t_{ichange}) of four seconds and is met by all vehicles tested. t_{c} and t_{e} are in the same range for the tested vehicles. Table 3.2 also provides ramp-up and -down values in kW/s for easier understanding. Here, it can be seen that asymmetric behavior is a common feature. The Nissan brand is much closer to having symmetric behavior.

3.3.4 Control and aggregation of AC charging dynamics

The delivery of a frequency service, e.g. frequency containment reserve for disturbance operation (FCR-D), requires a relatively fast control approach. According to the Nordic regulation, the injected power should be greater than zero within 2.5 seconds and the full bid delivered within 7.5 seconds [94].

In Denmark, the minimum threshold for a commercial aggregator to engage in the FCR-D market is set at 100 kW. Meeting this requirement necessitates the aggregation of multiple EVSEs to collectively fulfill the market bid, a challenging task when orchestrating multiple clusters of EVSEs to deliver a frequency service.

To comply with the stringent 2.5-second control loop delay requirement and ensure ramping rates meeting the 7.5-second standard, a comprehensive consideration of the entire control loop's combinations is imperative. Figure 3.11 summarizes the demonstration results of the FCR-D pre-qualification process with a centralized control approach using ACDC smart EVSE and two identical Renault Zoe 40. The analysis reveals that controlling an EVSE cluster induces greater delays in the control loop compared to managing a singular EVSE. In the current ACDC cloud setup, the process takes up to six seconds to receive and compute new active power set points for the charging cluster. Notably, a significant portion of this delay (six seconds) results from unoptimized control algorithms and communication with external servers within the cloud intelligence.

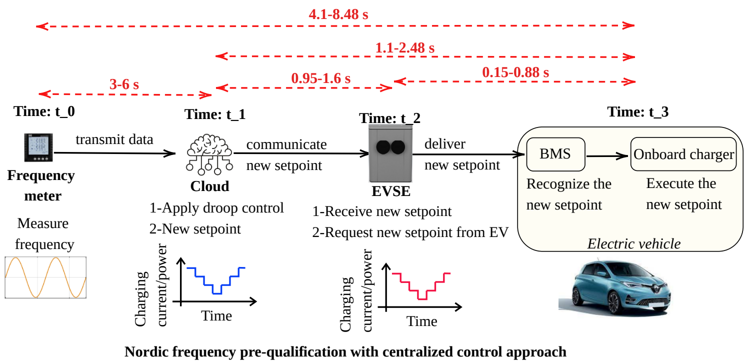


Figure 3.11: Demonstration of Nordic frequency service delivery pre-qualification process with a cluster of chargers and two homogeneous Renault Zoe 40.

Table 3.2: Modeling data for electric vehicle onboard charger based on experimental validations.

Vehicle	**Max/min ch.current**	**Ramp-up per phase [A/s]**	**Ramp-up [kW/s]**	**Ramp-down per phase [A/s]**	**Ramp-down [kW/s]**	**t_a [s]**	**t_b [s]**	**t_c [s]**	**t_d [s]**	**t_e [s]**	**t_f [s]**	**t_g [s]**
VW ID3 Pro (2023) 58 kWh	16/6	14.54	10.03	114.28	78.85	2.54	1.1	0.78	0.14	0.78	0.94	0.14
Nissan Arya (2022) 87 kWh	32/6	9.55	6.59	18.2	12.55	0.5	4	0.02	1.35	0.02	2.55	1.5
Nissan LEAF e+ (2022) 62 kWh	32/6	25	5.75	21.8	5.01	3.6	1.28	0.03	1.19	0.03	1.05	0.23
Skoda Enyaq iV 60 (2021) 62 kWh	16/6	13.3	9.17	160	110.4	2	1.2	0.68	0.1	0.68	0.84	0.1
Tesla M3 LRDM (2020) 78.1 kWh	16/6	1.06	0.73	800	552	2	15	0.02	0.02	0.02	8	0.02
Renault Zoe 40 (2018) 44.1 kWh	32/6	8.8	6.13	40	27.6	3.8	3.6	0.1	1.25	0.65	2.78	0.5

The overall control delay, from the detection of a frequency deviation to the injection of power, spans between 4.1 to 8.48 seconds. When scrutinizing the delay between the cloud signaling a new power setpoint and the vehicle response, the duration ranges from 1.1 to 2.48 seconds. Here, the small response delay of the vehicle's OBC corresponds to modulating up or down 2 A. Consequently, this proves that, with an optimized cloud computing system, it is possible to achieve FCR-D delivery with Renault Zoe 40.

CHAPTER 4

Smart charging benefits and implications

4.1 Smart charging strategies

Previous chapters described AC charging technology, the framework for providing grid services with EVs and the technical solutions to control and aggregate the AC charging process of EV. This chapter completes the picture by providing economic (from the end-user perspective) and technical (from the power grid perspective) results. The former is based on the research done at **Paper** [**P7**] on Danish soil and the latter is based on the investigation from **Paper** [**P8**] performed in Norwegian soil.

Before diving into the results of smart charging, it is necessary to explain the smart charging strategies. The main object of a smart charging strategy is to adjust the charging process in response to external economic or technical signals, according to the EV owner's wishes, to increase the power grid resilience and achieve economic profitability. Smart charging strategies are divided as behind and front-of-the-meter.

Depending on the strategy aim, single or stacked grid services, it is important to analyze the input information required and DSO-TSO interaction for designing a strategy.

4.2 Residential EVs smart charging in Denmark

4.2.1 System architecture

As previously mentioned, during the ACDC research project, a novel smart EVSE was developed, which employs a distributed control architecture. The entire system architecture is presented in Fig. 4.1. The smart EVSE designed in the ACDC research project is comprised of two groups of components, i) the charging component: the protection and charging port, and ii) the virtual aggregator component: the charger intelligence.

The system accounts for a residential household with a rooftop PV system, and an EV with possibility to be controlled with a VA. The VA: i) retrieves signals of total power flow for the entire system at the metering point, ii) downloads price and emission prognosis data from Nordpool and Energinet, and iii) receives the initial battery level, the energy requested at the plug-out time, and EV plug-in/out times from the EV owner. In the following, the intelligence of EVSE optimizes the charging process according to the chosen smart charging strategy.

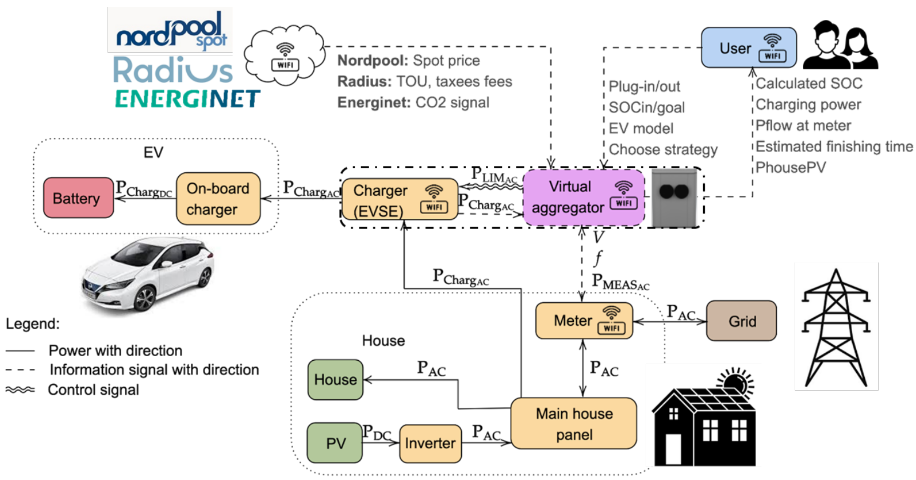


Figure 4.1: Overview of the smart charging system architecture.

Three smart charging goals are considered: i) charge during hours with the lowest electricity price, ii) lower emission footprint and thus lessen the demand for carbon-intensive generating units, or iii) increase self-consumption by charging during PV production and therefore reduce demand from the grid. The first two consider external parameters, that is, electricity price and CO2 emissions, while the last strategy only focuses on the residential system behind the meter.

4.2.2 Data availability

In contrast to other similar studies, all smart charging strategies are tested considering real EV user behavior in terms of plug-in/out times and varying energy demands. A survey was conducted for 14 owners EV who resided in Denmark during November and December 2019 to understand their charging behavior. The information included is battery size, SOC in plug-in and plug-out, plug-in / plug-out time, and charging location, namely: home, work, or elsewhere. The charging patterns were classified into three groups of similar behavior with respect to energy demand versus connection time, charging frequency, and battery SOC at plug-in (SOC_{IN}).

A representative pattern is chosen from each group and named G1, G2, and G3. These groups represent EV owners with different connection times. In G1, EV owners use the vehicle every day, plug in once they arrive home (independently of the battery level), and do not disconnect until EV is used again. In G2, EV is connected one or two nights a week and thus is charged less frequently. In this group, users connect and charge their vehicles only if SOC is less than 25%. In G2, vehicles on average have a higher demand per charging event than in G1. Lastly, G3 represents the least flexible group, where vehicles are charged up to once a week and connected to the charger only for a limited amount of time.

A graphical example of charging times for an arbitrary week and each representative pattern is provided in Figure 4.2. For simplicity, the three groups are considered to have the same battery size of 75 kWh and a charging power of 11.04 kW (6-16 A as limiting currents) with 80% charging efficiency at 6 A and 90% at 16 A. As the case study is for the entire year 2020, charging connection times are considered to be the same for the 12 months. However, seasonal variations that affect energy consumption are incorporated by varying SOC_{IN} from vehicle efficiency data [95].

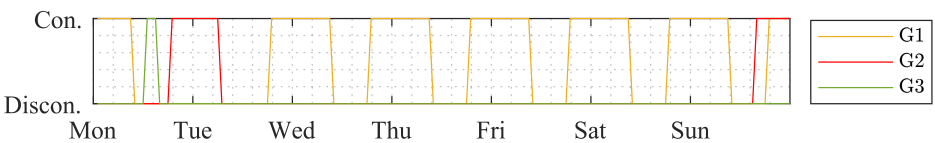


Figure 4.2: EV plug-in/ plug-out patterns group G1 (average distance driven between charging events 80 km), G2 (218 km), and G3 (75 km).

Data for household consumption and PV production of a 6 kWp PV plant are taken from a representative household in Denmark for 2020. The data are provided with a 5-minute resolution; more details are given in [96]. The hourly spot prices are retrieved from NordPool [97]. The time of use (ToU) tariffs are extracted from the largest DSO in Denmark, Radius, and its price scheme for residential homes [98]. The emission prognosis data are collected from Energinet [99], [100] for East Denmark grid region (DK2) and have a resolution of 5 minutes. Sunny hours are defined based on data from the Danmark Meteorologiske Institut [101] and PV production data from the house system with respect to sunrise, sunset and production hours.

4.2.3 Results of residential smart charging strategies in Denmark

Before presenting the results (for more details, see **Paper [P7]**), it is valuable to mention the goal of each smart charging strategy. The base strategy reflects the behavior of the users surveyed, who do not employ any smart technology in their daily activities. The price-based strategy reflects EV charging according to an electricity price signal. This includes both the spot price based on the day-ahead market and the ToU tariffs. The emission-based strategy aims to minimize the carbon footprint by charging during periods of lower carbon levels in the grid. As actual emission can vary from its prognosis, two methods are considered:

- CO2 Case 1): charge only during periods of lowest predicted emission levels.
- CO2 Case 2): vary the charging power according to the predicted emission level.

Figure 4.3 presents a comprehensive breakdown of the charging costs under emission-based strategies and the resulting levels of carbon dioxide (CO2) when the charging is based on the price-based strategy. The analysis reveals a correlation between low emission hours and low electricity price. Employing a control signal aligned with emission forecasts can minimize charging expenses, and conversely. The initial emission strategy (CO2 Case 1) shows a considerable cost reduction in all groups, with the most significant decrease observed at 253 euros for G1. The subsequent emission-based strategy (C02 Case 2) illustrates a lower cost reduction across all groups. Furthermore, both the G1-Price-based and G2-Price-based categories indicate lower cumulative CO2 levels compared to the CO2 Case 2 counterpart. These findings underscore the tangible connection between electricity price and CO2 emissions within the current Danish power system.

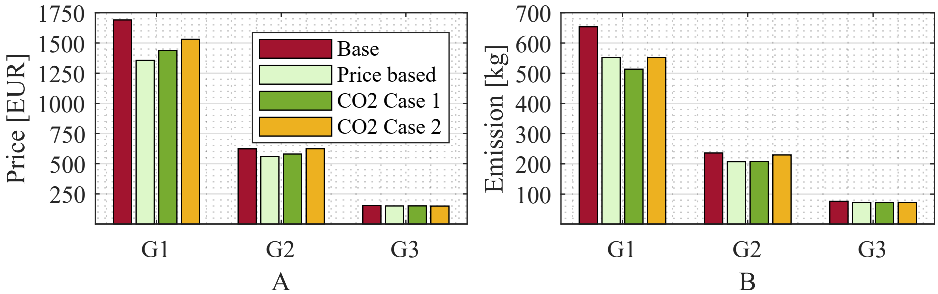


Figure 4.3: (A) Cost and (B) emission for one year of charging for all groups when using different smart charging strategies.

Table 4.1 provides a comparative analysis of annual costs for 2020 and 2021 electricity prices under the scenarios of dumb charging and price-based strategies. For 2020, with the price-based strategy, EV owner charging costs decreased by 19.8% for G1, 10.1% for G2, and 3.3% for G3. Whereas, for 2021, with the price-based strategy, EV owner charging costs decreased further by 24.8% for G1, 14.9% for G2, and 5.4% for G3. In particular, smart daily charging emerges as the option leading to the most significant savings compared to dumb daily charging.

Table 4.1: Charging costs with price based strategy for 2020 and 2021.

Group	**2020 Base [€]**	**2020 Smart [€]**	**2021 Base [€]**	**2021 Smart [€]**
G1	1692	1358	2219	1670
G2	624	561	849	723
G3	155	150	207	196

In summary, for the price-based strategy, G1 (EV users who plug in every night) and G2 (EV users who plug in once / twice a week overnight) have a noticeable reduction in costs. The emission-based strategy has a similar maximum drop, 21% with G1 being the largest. The use of price or emission strategies reduces both costs and emissions. Most importantly, both strategies point to the benefit of a longer overnight connection and more frequent charging events. The results are the opposite for the self-consumption based strategy. There is only a negligible change in the results for vehicles that connect more often and during the night. However, an economic growth of 12% could be achieved by connecting the vehicle once a week during the daytime hours. This suggests the success of the strategy for consumers who ensure that EV is connected during the day. Lastly, higher electricity costs in 2021 resulted in an increase of 30-35% in the cost of dumb charging.

4.3 Smart charging implications-Norwegian case

4.3.1 Context and data availability

Norway is a leader in terms of the adoption of electric mobility. Hence, it serves as a testbed for the future implications of electric mobility. This is the case with the charging of EVs. Previous investigations have demonstrated challenges that can be summarized into two main issues, energy and instantaneous power requirements [102], [103]. Although the energy needs of electric mobility are not a problem [103], [104], instantaneous power can become a tall challenge to the power system, particularly at the distribution grid level [102].

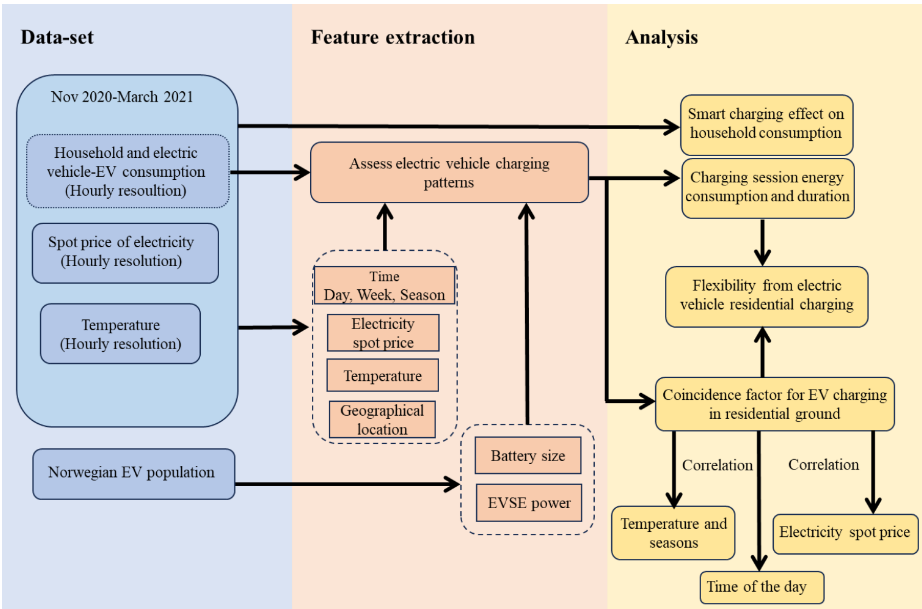


Figure 4.4: Work flow followed in investigating the Norwegian residential charging behavior.

Advances in communication and control of EVSEs bring more possibilities for automation and greater acceptance for smart charging strategies, similar to Tibber (energy supplier) in Norway. However, automation combined with market synchronization can exacerbate the instantaneous power challenge by creating avalanche (new higher peaks) and rebound effects [22]. To understand the possibility of synchronization, it is important to understand the charging CF. CF quantifies the ratio of EVs charging at the same exact moment compared to the entire EV fleet.

Figure 4.4 describes the data set available from Norwegian customers of the energy supplier Tibber. The investigation analyzes a data set of 216 households who own a Tesla electric vehicle and a remotely controllable smart EVSE to minimize the cost to consumers using an hourly electricity tariff. The data run from November 2020 to March 2021 and covers customers from all five Norwegian bidding zones that display both dumb (normal) and smart charging behavior. Tibber is one of the few energy suppliers to offer smart charging programs to their customers. Therefore, it gives the possibility of better understanding the evolution of CF from natural to smart charging.

4.3.2 Factors influencing charging coincidence factor

The traditional grid planning process involves selecting grid components that can meet the system's maximum demand and typically have a lifespan ranging from 25 to 50 years [105]. To understand the impact that electric mobility would have on the instantaneous active power requested, it is necessary to quantify CF. Instantaneous active power for electric mobility can violate the limits of the operation of the power grid, thus demanding new investments in the power grid.

The authors of [21] suggest that natural domestic CF is affected by: i) the size of the EV fleet considered, ii) the pool of EV models and the size of the battery in the EV fleet, iii) the power of the charger, and iv) driving patterns. Furthermore, the results highlighted a correlation between the increase in the number of EVs in the fleet and the reduction of CF. The investigation of Tibber data in Norway suggests that CF is influenced even by i) geographical location (flat, hilly or mountainous terrain), ii) time, iii) economic incentives, and iv) weather. The terrain influences the consumption of the EV fleet, where a more mountainous terrain would consume more energy than a flat terrain. This can be seen by comparing the average energy delivered per session in Norway (21 kWh) and Denmark (17 kWh). On average, from the available data, EV users in both countries drive the same daily distance.

Figure 4.5 presents the charging CF of normal (natural), smart and all customers from Tibber data in Norway. The boxplots show the distribution of CF during the day and during the week. The first row displays the CF distribution over the course of a day and a week of customers who use Tibber's smart charging strategy. The second row shows the CF distribution over the course of a day and a week from normal (natural) Tibber customers. The calculated natural charging CF in residential ground indicates more connected vehicles during the evening and night. However, the distribution values are below 15% and hour 02:00 has the highest value as an outlier at 13%. Consequently, Friday is the day with the highest simultaneous charging sessions for normal customers. This can be explained with a common behavior of charging before weekend trips.

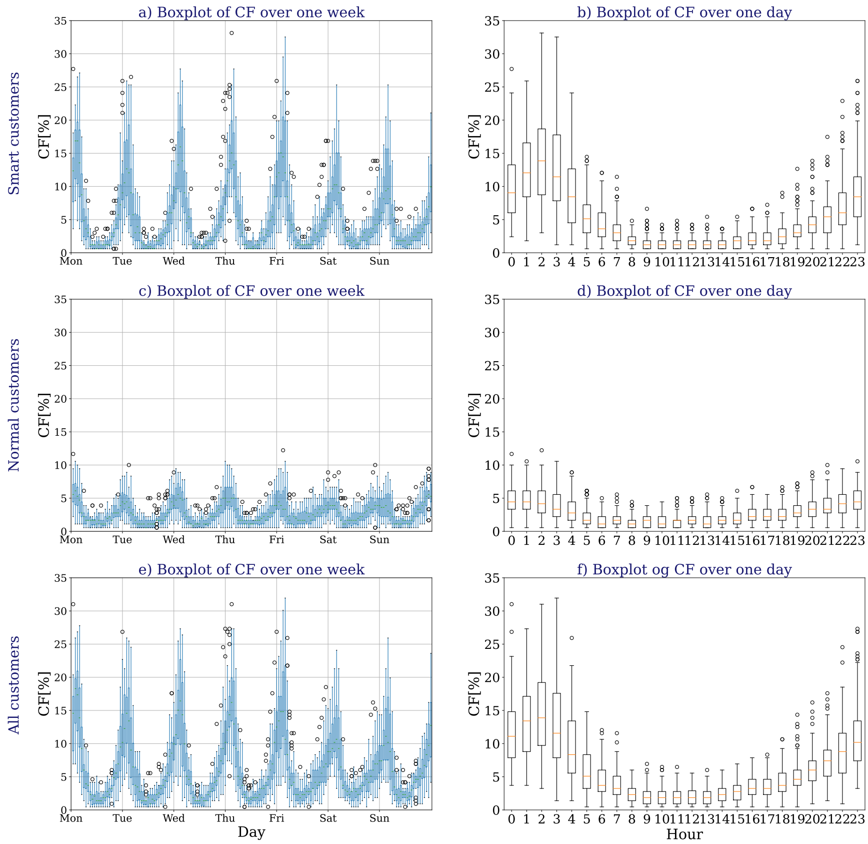


Figure 4.5: Row one shows boxplots of the CF for each hour over the course of a week. In row two the boxplots over 24 hours are plotted. The rows include smart charging, normal charging and all charging in row one, two and three respectively.

In comparison, residential customers with smart charging behavior exacerbate the charging CF during evening and night time. The charging CF at hour 02:00

can reach 32%. Similar to natural charging, Friday is again the day with the highest simultaneous charging events for smart residential customers. Notably, smart customers are economically motivated to synchronize their charging behavior with periods of lower electricity prices. So far, this synchronization is still in early stages and is happening in an hourly basis. In light of such synchronized behavior, the power avalanche effect challenge arises. Subsequently, smart charging synchronization should be mitigated and possible spread throughout the day. Following this, Fig. 4.6 compares charging CF with electricity spot price and temperature. Data support previous claims and highlight a negative correlation between charging CF and the electricity spot price.

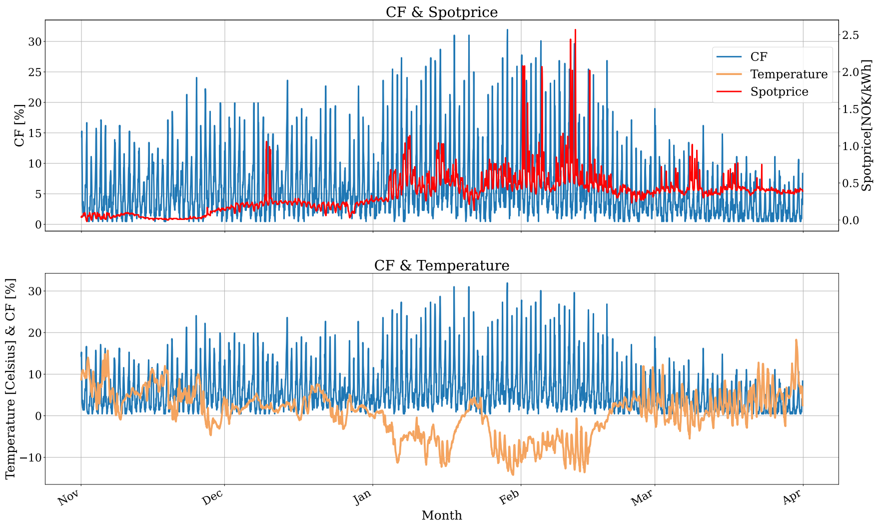


Figure 4.6: Plots of CF and spot price (top), and CF and temperature (bottom) for November through April.

In a similar way, there exists a negative correlation between charging CF and temperature. During the cold season, there is a higher demand for charging energy. Consequently, there are longer and more frequent charging sessions. To illustrate, one can observe the change in CF from February to March in Fig. 4.6. Colder temperatures correlate with larger CF and as soon as the temperature rises to above zero, the value of CF reduces. Although the data do not stretch in the summer period, a similar behavior towards a second peak of energy demand is expected. However, the effect in the colder season should be significantly higher.

As a final point, the normal (natural) residential charging behavior does not extend over 15% CF. On the contrary, smart residential charging CF can reach up to 32% due to electricity price synchronization. These values agree with a recent study [22] and it is important to highlight that synchronization of large fleets can harm the low and medium voltage power grid.

CHAPTER 5

Conclusion

5.1 Summary

EVs and their AC charging operation is an untapped source of much-needed demand-side flexibility that can create synergies between the transportation and power sectors. Although the principles of power system flexibility are well defined, the delivery of a flexibility service has yet to mature.

Therefore, this thesis started its investigation by designing a framework for delivering a flexibility service, with a special focus on EVs. Based on a comprehensive review of the literature and industrial practices, the following definiton was proposed: *Flexibility service refers to scheduling and/or modulation of the collective/single consumption or generation of electrical appliances or distributed technologies, in agreement with the client (consumer or generator) or mandated in the grid code, in response to signals from market enablers, to increase the network reliability and efficiency on a predefined time and location.* Following this, the entire process of delivering a flexibility solution should incorporate five principles:

1. Interoperability: Consumers should have the possibility of choosing from different flexibility providers.
2. Data privacy: Personal data should be used under clear consent agreements and remain secure/encrypted by flexibility providers.
3. Cyber security: Confidentiality and control services of smart appliances should never be breached by an unauthorized user.
4. Grid stability: Each activation of the flexibility service should not compromise the stability and resilience of the grid.
5. Transparency and fairness: System operators and market enablers should provide standardized guidelines to all participating actors.

Given that the delivery of the grid services from EV will mature, it is important to understand their geographical distribution within the grid along with their technological capabilities. For example, EVs charging stations can be connected at different voltage levels in the power grid. Therefore, the thesis presented the supply chain of flexibility services from EVs that counted seven actors and 12 possible charging clusters.

With regard to technological capabilities, the thesis looks at the slow AC charging process that requires the combination of the EVSE and vehicle OBC. In this context, the electrical characteristics (AC-to-DC conversion efficiency, reactive power, and PF) of 38 different light-duty EV OBCs of the past 11 years are analyzed. Three-phase EVs have higher efficiency (87-90%) than single-phase (78-88%) EVs. However, curtailed three-phase EVs have efficiency (78-87%) similar to single-phase EVs. By 2030, the EV fleet could achieve efficiency values of 88-95% and the OBC technology efficiency could saturate by 2035 to a value of 90-96%. Regarding reactive power consumption, very few vehicle types violate the low-voltage network code by experiencing a PF smaller than 0.9 when charging with a current below 10 A. However, to further promote smart charging, the power factor correction units of OBCs should be optimized for the entire charging range.

For the second part of technological capabilities, the thesis investigated the EVSE and OBC control capabilities. The state-of-the-art for a smart EVSE can be described as *an electric device providing protection, communication, at least scheduling and at most modulation, phase curtailment (3 to 1-phase switch) and phase switching for the EV charging process.* Moreover, the control delay between an aggregator entity (such as a CPO) and the EV can be divided into two parts. The delay between CPO-EVSE and EVSE-vehicle OBC. The former relies on the quality of the EVSE manufacturer, CPO backend applications, and the standard communication limitations. The latter is based on technological improvements from the automakers. Three different EVSE communication topologies (WiFi, OCPP, and 4G) are tested and measured against their reaction speed. The data suggest that OCPP 1.6J communication might be delay-prone due to heavier data transactions and security. However, experimental results show that it is possible to reach a delay below one second between CPO-EVSE, with specific vehicle brands. This highlights the large differences in the control and dynamic behavior of EVs. In the final analysis, if CPO wants to provide grid service by stopping charging operations, it can be achieved by controlling EVSE in less than 0.5 seconds. However, restarting the charging process would require significantly more time, and that might compromise the linearity and symmetric requirements for delivering a grid service.

Finally, the last part of the thesis presented results from real-life smart residential charging scenarios from Denmark and Norway. The former looks at the

EV owner's economic benefits when employing smart charging strategies. Smart charging focused on cost reduction for the years 2020 and 2021, and produced savings for the EV owners up to 334 €/year and 549 €/year, respectively. The 2020 emission reduction strategy reduced the emissions by 240 kg CO_2/year. Consequently, such numbers can be higher if the aggregator entities enter even the grid services market, since they can offer smart charging strategies to EV end-users by aggregating a large number of EVs. Furthermore, the Norwegian smart charging scenario investigated the implications of synchronizing the charging behavior on a large scale due to external control signals (such as the electricity price). The size of vehicles that charge simultaneously, also known asCF, increases during times of low electricity prices for customers that use a smart charging scheme, compared to the customers with a natural charging behavior. With this in mind, it is of paramount importance to carefully design smart charging strategies that are aware of the power grid constraints. However, a promising observation is that in Norway, on average, a residential charging session lasts at least four hours and delivers 21 kWh with an EVSE power of 6.37 kW (or 16 A). Hence, on average, there are always at least 40 minutes of flexibility during the residential four-hour charging process.

5.2 Perspectives for future research

The thesis elevated knowledge and state-of-the-art in the delivery of EV grid services from AC charging. One the one hand, having a map of ancillary services coupled with EVs charging clusters opens up the door to fully exploit smart charging strategies. On the other hand, it provides to stakeholders the possibility to better understand their roles. However, the available flexibility of each charging clusters needs to be further investigated and quantified. The Nordic case highlights the need for simple regulations to attract flexibility providers.

Outside of regulatory challenges that need to be addressed further, there are also technological challenges. For instance, in light of the results on smart charging efficiency, there is a growing demand to design a European efficiency regulation for the full charging sessions (0-100% SOC) similar to the European PV inverter efficiency. Subsequently, future work should focus on expanding the investigation to other automakers, with a special focus on 800 V architecture models, and analyzing the harmonic disturbance of OBCs. In addition, there is a high demand for better energy simulation models that include EV efficiency. Better results can be achieved by considering the efficiency curve of each vehicle; however, such an approach can significantly increase the computational requirements. Thus, implementing the aggregated efficiency curve is a more feasible computational solution.

Another technical challenge is the IEC 61851 standard, which only quantifies an upper-limit charging current. This approach hampers the participation of EV fleets into electricity markets, because the BMS decides on its own how much charging current the OBC should draw; hence creating uncertainty in the charging behaviour. Here, a solution can be the online optimization of the charging demand based on real-time meter readings. With regard to the EVSE - vehicle OBC control speed, the IEC 61851-1 standard does not encourage fast control loops. The lack of standardization is restraining the development of resilient, fast, and future-proof control and communication. Most of the EVSEs technology is based on cloud communications; hence, they have a single point of failure. The ACDC EVSE with the distribution approach serves as an example of mitigating a single point of failure for such a large energy infrastructure. As a final remark on control and communication for the EVSE, a more thorough investigation is needed for the communication speed of the new OCPP standard.

Bibliography

[1] *The Paris Agreement*. URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[2] IEA. *Global energy-related CO2 emissions by sector*. IEA, Paris. URL: https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector.

[3] H. Kondziella and T. Bruckner. "Flexibility requirements of renewable energy based electricity systems - A review of research results and methodologies." In: *Renewable and Sustainable Energy Reviews* 53 (2016), pages 10–22. DOI: 10.1016/j.rser.2015.07.199.

[4] M. Sencar, V. Pozeb, and T. Krope. "Development of EU (European Union) energy market agenda and security of supply." In: *Energy* 77 (2014), pages 117–124. DOI: 10.1016/j.energy.2014.05.031.

[5] P. Kundur, J. Paserba, V. Ajjarapu, et al. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions." In: *IEEE transactions on Power Systems* 19 (2004), pages 1387–1401.

[6] N. Hatziargyriou, J. Milanovic, C. Rahmann, et al. "Definition and classification of power system stability revisited & extended." In: *IEEE Transactions on Power Systems* (2020).

[7] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou. "Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems." In: *IEEE Transactions on Power Systems* 32 (2017), pages 4732–4742. DOI: 10.1109/TPWRS.2017.2664141.

[8] L. Calearo, M. Marinelli, and C. Ziras. "A review of data sources for electric vehicle integration studies." In: *Renewable and Sustainable Energy Reviews* 151 (2021), page 111518.

[9] S. Misconel, C. Zöphel, and D. Möst. "Assessing the value of demand response in a decarbonized energy system–A large-scale model application." In: *Applied Energy* 299 (2021), page 117326.

[10] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida. "Integration of electric vehicles in the electric power system." In: *Proceedings of the IEEE* 99 (2010), pages 168–183.

[11] F. G. Venegas, M. Petit, and Y. Perez. "Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services." In: *Renewable and Sustainable Energy Reviews* 145 (2021), page 111060.

[12] L. Calearo, A. Thingvad, K. Suzuki, and M. Marinelli. "Grid loading due to EV charging profiles based on pseudo-real driving pattern and user behavior." In: *IEEE Transactions on Transportation Electrification* 5 (2019), pages 683–694.

[13] M. Z. Degefa, I. B. Sperstad, and H. Sæle. "Comprehensive classifications and characterizations of power system flexibility resources." In: *Electric Power Systems Research* 194 (2021), page 107022.

[14] H. Sæle and I. Petersen. "Electric vehicles in Norway and the potential for demand response." In: *2018 53rd International Universities Power Engineering Conference (UPEC)*. IEEE. 2018, pages 1–6.

[15] M. Marinelli, K. Sevdari, L. Calearo, A. Thingvad, and C. Ziras. "Frequency stability with converter-connected resources delivering fast frequency control." In: *Electric Power Systems Research* 200 (2021), page 107473.

[16] International Electrotechnical Commission. *IEC 61851*. 2017. URL: https://webstore.iec.ch/publication/33644.

[17] H. Wouters and W. Martinez. "Bidirectional On-Board Chargers for Electric Vehicles: State-of-the-Art and Future Trends." In: *IEEE Transactions on Power Electronics* (2023).

[18] A. Thingvad, L. Calearo, P. B. Andersen, et al. "Value of V2G frequency regulation in Great Britain considering real driving data." In: *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*. IEEE. 2019, pages 1–5.

[19] A. Thingvad, C. Ziras, and M. Marinelli. "Economic value of electric vehicle reserve provision in the Nordic countries under driving requirements and charger losses." In: *Journal of Energy Storage* 21 (2019), pages 826–834.

[20] L. Calearo and M. Marinelli. "Profitability of frequency regulation by electric vehicles in Denmark and Japan considering battery degradation costs." In: *World Electric Vehicle Journal* 11 (2020), page 48.

[21] J. Bollerslev, P. B. Andersen, T. V. Jensen, et al. "Coincidence factors for domestic ev charging from driving and plug-in behavior." In: *IEEE Transactions on Transportation Electrification* 8 (2021), pages 808–819.

[22] T. Unterluggauer, F. Hipolito, J. Rich, M. Marinelli, and P. B. Andersen. "Impact of cost-based smart electric vehicle charging on urban low voltage power distribution networks." In: *Sustainable Energy, Grids and Networks* (2023), page 101085.

[23] T. Unterluggauer, F. Hipolito, S. Klyapovskiy, and P. B. Andersen. "Impact of Electric Vehicle Charging Synchronization on the Urban Medium Voltage Power Distribution Network of Frederiksberg." In: *World Electric Vehicle Journal* 13 (2022), page 182.

[24] S. Rivera, S. Kouro, S. Vazquez, S. M. Goetz, R. Lizana, and E. Romero-Cadaval. "Electric vehicle charging infrastructure: From grid to battery." In: *IEEE Industrial Electronics Magazine* 15 (2021), pages 37–51.

[25] A. Khaligh and M. D'Antonio. "Global trends in high-power on-board chargers for electric vehicles." In: *IEEE Transactions on Vehicular Technology* 68 (2019), pages 3306–3324.

[26] C.-H. Lo and N. Ansari. "Decentralized controls and communications for autonomous distribution networks in smart grid." In: *IEEE transactions on smart grid* 4 (2012), pages 66–77.

[27] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki. "Taxonomy for Evaluation of Distributed Control Strategies for Distributed Energy Resources." In: *IEEE Transactions on Smart Grid* 9 (2018), pages 5185–5195. DOI: 10.1109/TSG.2017.2682924.

[28] P. Richardson, D. Flynn, and A. Keane. "Local versus centralized charging strategies for electric vehicles in low voltage distribution systems." In: *IEEE Transactions on Smart Grid* 3 (2012), pages 1020–1028. DOI: 10.1109/TSG.2012.2185523.

[29] S. Striani, K. Sevdari, P. B. Andersen, M. Marinelli, Y. Kobayashi, and K. Suzuki. "Autonomously distributed control of ev parking lot management for optimal grid integration." In: *2022 International Conference on Renewable Energies and Smart Technologies (REST)*. Volume 1. IEEE. 2022, pages 1–5.

[30] S. Striani, K. Sevdari, M. Marinelli, V. Lampropoulos, Y. Kobayashi, and K. Suzuki. "Wind Based Charging via Autonomously Controlled EV Chargers under Grid Constraints." In: *2022 57th International Universities Power Engineering Conference (UPEC)*. IEEE. 2022, pages 1–6.

[31] C. Ziras, A. M. Prostejovsky, H. W. Bindner, and M. Marinelli. "Decentralized and discretized control for storage systems offering primary frequency control." In: *Electric Power Systems Research* 177 (March 2019), page 106000. DOI: 10.1016/j.epsr.2019.106000.

[32] L. Gan, U. Topcu, and S. H. Low. "Optimal decentralized protocol for electric vehicle charging." In: *IEEE Transactions on Power Systems* 28 (2013), pages 940–951. DOI: 10.1109/TPWRS.2012.2210288.

[33] C. Alcaraz, J. Lopez, and S. Wolthusen. "OCPP protocol: Security threats and challenges." In: *IEEE Transactions on Smart Grid* 8 (2017), pages 2452–2459.

[34] Open Charge Alliance. *Open Charge Point Protocol 2.0*. 2018. URL: https://www.openchargealliance.org/protocols/ocpp-201/.

[35] T. Mai, M. M. Hand, S. F. Baldwin, et al. "Renewable electricity futures for the United States." In: *IEEE Transactions on Sustainable Energy* 5 (2013), pages 372–378.

[36] U. Tamrakar, D. Shrestha, M. Maharjan, and B. P. Bhattarai. "Virtual Inertia : Current Trends and Future Directions." In: *applied sciences* (2017), pages 1–29. DOI: 10.3390/app7070654.

[37] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič. "Foundations and challenges of low-inertia systems." In: *2018 Power Systems Computation Conference (PSCC)*. IEEE. 2018, pages 1–25.

[38] F. Díaz-González, M. Hau, A. Sumper, and O. Gomis-Bellmunt. "Participation of wind power plants in system frequency control: Review of grid code requirements and control methods." In: *Renewable and Sustainable Energy Reviews* 34 (2014), pages 551–564.

[39] P. Tielens and D. Van Hertem. "The relevance of inertia in power systems." In: *Renewable and Sustainable Energy Reviews* 55 (2016), pages 999–1009. DOI: 10.1016/j.rser.2015.11.016.

[40] F. Gonzalez-Longatt. "Frequency control and inertial response schemes for the future power networks." In: *Large scale renewable power generation*. Springer, 2014, pages 193–231.

[41] M. Rezkalla, M. Pertl, and M. Marinelli. "Electric power system inertia: requirements, challenges and solutions." In: *Electrical Engineering* 100 (2018), pages 2677–2693. DOI: 10.1007/s00202-018-0739-z.

[42] H. T. Nguyen, M. N. Chleirigh, and G. Yang. “A Technical Economic Evaluation of Inertial Response from Wind Generators and Synchronous Condensers.” In: *IEEE Access* 9 (2021), pages 7183–7192. DOI: 10.1109/ACCESS.2021.3049197.

[43] R. Eriksson, N. Modig, and K. Elkington. “Synthetic inertia versus fast frequency response: a definition.” In: *IET Renewable Power Generation* 12 (2018), pages 507–514.

[44] M. Rezkalla, A. Zecchino, S. Martinenas, A. M. Prostejovsky, and M. Marinelli. “Comparison between synthetic inertia and fast frequency containment control based on single phase EVs in a microgrid.” In: *Applied Energy* 210 (2018), pages 764–775.

[45] Y. Zuo, Z. Yuan, F. Sossan, A. Zecchino, R. Cherkaoui, and M. Paolone. “Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids.” In: *Sustainable Energy, Grids and Networks* 27 (2021), page 100496. DOI: 10.1016/j.segan.2021.100496.

[46] U. Tamrakar, D. Shrestha, M. Maharjan, B. P. Bhattarai, T. M. Hansen, and R. Tonkoski. “Virtual inertia: Current trends and future directions.” In: *Applied Sciences* 7 (2017), page 654.

[47] “Applying Synchronous Condenser for Damping Provision in Converter-dominated Power System.” In: *Journal of Modern Power Systems and Clean Energy* 9 (2021), pages 639–647.

[48] M. Marinelli, K. Sevdari, L. Calearo, A. Thingvad, and C. Ziras. “Frequency stability with converter-connected resources delivering fast frequency control.” In: *Electric Power Systems Research* 200 (2021), page 107473. DOI: 10.1016/j.epsr.2021.107473.

[49] Statnett. *Fast Frequency Reserves 2018 - pilot for raske frekvensreserver*. Technical report. 2018, pages 1–36.

[50] A. Thingvad, C. Ziras, and M. Marinelli. “Economic value of electric vehicle reserve provision in the Nordic countries under driving requirements and charger losses.” In: *Journal of Energy Storage* 21 (2019), pages 826–834. DOI: 10.1016/j.est.2018.12.018.

[51] M. Marinelli, S. Martinenas, K. Knezović, and P. B. Andersen. “Validating a centralized approach to primary frequency control with series-produced electric vehicles.” In: *Journal of Energy Storage* 7 (2016), pages 63–73.

[52] TenneT TSO B.V. “aFRR pilot end report.” In: (2021), pages 1–37.

[53] H. Fan, L. Jiang, C. K. Zhang, and C. Mao. "Frequency regulation of multi-area power systems with plug-in electric vehicles considering communication delays." In: *IET Generation, Transmission and Distribution* 10 (2016), pages 3481–3491. DOI: 10.1049/iet-gtd.2016.0108.

[54] Statnett SF. "Distributed balancing of the power grid." In: (2021), pages 1–48.

[55] T. Aigner, S. Jaehnert, G. L. Doorman, and T. Gjengedal. "The effect of large-scale wind power on system balancing in Northern Europe." In: *IEEE Transactions on Sustainable Energy* 3 (2012), pages 751–759.

[56] D. Duckwitz and B. Fischer. "Modeling and design of df/dt-based inertia control for power converters." In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* 5 (2017), pages 1553–1564.

[57] J. Liu, Y. Miura, H. Bevrani, and T. Ise. "Enhanced virtual synchronous generator control for parallel inverters in microgrids." In: *IEEE Transactions on Smart Grid* 8 (2016), pages 2268–2277.

[58] G.-S. Seo, M. Colombino, I. Subotic, B. Johnson, D. Groß, and F. Dörfler. "Dispatchable virtual oscillator control for decentralized inverter-dominated power systems: Analysis and experiments." In: *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE. 2019, pages 561–566.

[59] J. Matevosyan, J. MacDowell, N. Miller, et al. "A future with inverter-based resources: Finding strength from traditional weakness." In: *IEEE Power and Energy Magazine* 19 (2021), pages 18–28.

[60] E. Akhavan-Rezai, M. Shaaban, E. El-Saadany, and A. Zidan. "Uncoordinated charging impacts of electric vehicles on electric distribution grids: Normal and fast charging comparison." In: *2012 IEEE power and energy society general meeting*. IEEE. 2012, pages 1–7.

[61] A. D. Hilshey, P. Rezaei, P. D. Hines, and J. Frolik. "Electric vehicle charging: Transformer impacts and smart, decentralized solutions." In: *2012 IEEE Power and Energy Society General Meeting*. IEEE. 2012, pages 1–8.

[62] M. Ghazavidozein, O. Gomis-Bellmunt, and P. Mancarella. "Simultaneous Provision of Dynamic Active and Reactive Power Response from Utility-scale Battery Energy Storage Systems in Weak Grids." In: *IEEE Transactions on Power Systems* (2021).

[63] P. Kundur. "Power system stability." In: *Power system stability and control* (2007), pages 7–1.

[64] H. F. Farahani, A. Rabiee, and M. Khalili. “Plug-in electric vehicles as a harmonic compensator into microgrids.” In: *Journal of Cleaner Production* 159 (2017), pages 388–396.

[65] A. M. Howlader, N. Urasaki, A. Yona, T. Senjyu, and A. Y. Saber. “A review of output power smoothing methods for wind energy conversion systems.” In: *Renewable and Sustainable Energy Reviews* 26 (2013), pages 135–146.

[66] E. Reihani, M. Motalleb, R. Ghorbani, and L. S. Saoud. “Load peak shaving and power smoothing of a distribution grid with high renewable energy penetration.” In: *Renewable energy* 86 (2016), pages 1372–1379.

[67] V. Monteiro, J. G. Pinto, B. Exposto, et al. “Assessment of a battery charger for electric vehicles with reactive power control.” In: *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society*. IEEE. 2012, pages 5142–5147.

[68] C. Brivio, S. Mandelli, and M. Merlo. “Battery energy storage system for primary control reserve and energy arbitrage.” In: *Sustainable Energy, Grids and Networks* 6 (2016), pages 152–165.

[69] M. Muratori, M. Alexander, D. Arent, et al. “The rise of electric vehicles—2020 status and future expectations.” In: *Progress in Energy* 3 (2021), page 022002. DOI: 10.1088/2516-1083/abe0ad.

[70] M. Klaes, A. Narayan, A. D. Patil, et al. “State description of cyber-physical energy systems.” In: *Energy Informatics* 3 (2020), pages 1–19. DOI: 10.1186/s42162-020-00119-3.

[71] S. M. Hussain, M. A. Aftab, I. Ali, and T. S. Ustun. “IEC 61850 based energy management system using plug-in electric vehicles and distributed generators during emergencies.” In: *International Journal of Electrical Power and Energy Systems* 119 (2020), page 105873. DOI: 10.1016/j.ijepes.2020.105873.

[72] H. Stian, A. Heidi, G. Hanne, and D. Espen. *Market based flexibility procurement for Nordic DSOs*. Technical report. 2021.

[73] British Standard Institution. *PAS 1879:2021, Energy smart appliances – Demand side response operation – Code of practice*. Technical report. 2021.

[74] Dansk Energi. *Industry guidance for network companies on procurement of flexibility services - first draft*. Technical report. 2021.

[75] E. Daramy-Williams, J. Anable, and S. Grant-Muller. “A systematic review of the evidence on plug-in electric vehicle user experience.” In: *Transportation Research Part D: Transport and Environment* 71 (2019), pages 22–36. DOI: 10.1016/j.trd.2019.01.008.

[76] L. Calearo, M. Marinelli, and C. Ziras. “A review of data sources for electric vehicle integration studies.” In: *Renewable and Sustainable Energy Reviews* 151 (2021). DOI: 10.1016/j.rser.2021.111518.

[77] E. Azadfar, V. Sreeram, and D. Harries. “The investigation of the major factors influencing plug-in electric vehicle driving patterns and charging behaviour.” In: *Renewable and Sustainable Energy Reviews* 42 (2015), pages 1065–1076. DOI: 10.1016/j.rser.2014.10.058.

[78] F. G. Venegas, M. Petit, and Y. Perez. “Plug-in behavior of electric vehicles users: Insights from a large-scale trial and impacts for grid integration studies.” In: *eTransportation* 10 (2021), page 100131. DOI: 10.1016/j.etran.2021.100131.

[79] I. S. Bayram, A. Saad, R. Sims, A. Babu, C. Edmunds, and S. Galloway. “Statistical characterisation of public AC EV chargers in the UK.” In: *IEEE Access* (2023).

[80] A. Tsakalidis, A. Julea, and C. Thiel. “The role of infrastructure for electric passenger car uptake in Europe.” In: *Energies* 12 (2019). DOI: 10.3390/en12224348.

[81] G. Falchetta and M. Noussan. “Electric vehicle charging network in Europe: An accessibility and deployment trends analysis.” In: *Transportation Research Part D: Transport and Environment* 94 (2021), page 102813. DOI: 10.1016/j.trd.2021.102813.

[82] T. Unterluggauer, J. Rich, P. B. Andersen, and S. Hashemi. “Electric vehicle charging infrastructure planning for integrated transportation and power distribution networks: A review.” In: *ETransportation* 12 (2022), page 100163.

[83] Enexis Netbeheer, Enpuls, ElaadNL, and MAXEM. “Charge Management of Electric Vehicles At Home.” In: (2020).

[84] C. Binding, D. Gantenbein, B. Jansen, et al. “Electric vehicle fleet integration in the Danish EDISON project - A virtual power plant on the island of Bornholm.” In: *IEEE PES General Meeting, PES 2010* (2010), pages 1–8. DOI: 10.1109/PES.2010.5589605.

[85] European commission. *Regulation (EU) 2019/943 on the internal market for electricity.* 2019.

[86] B. E. Lebrouhi, Y. Khattari, B. Lamrani, M. Maaroufi, Y. Zeraouli, and T. Kousksou. “Key challenges for a large-scale development of battery electric vehicles: A comprehensive review.” In: *Journal of Energy Storage* 44 (2021), page 103273. DOI: 10.1016/j.est.2021.103273.

[87] M. T. Hussain, D. N. B. Sulaiman, M. S. Hussain, and M. Jabir. "Optimal Management strategies to solve issues of grid having Electric Vehicles (EV): A review." In: *Journal of Energy Storage* 33 (2021), page 102114. DOI: 10.1016/j.est.2020.102114.

[88] A. García, J. Monsalve-Serrano, S. Martinez-Boggio, and S. Tripathi. "Techno-economic assessment of vehicle electrification in the six largest global automotive markets." In: *Energy Conversion and Management* 270 (2022), page 116273. DOI: 10.1016/j.enconman.2022.116273.

[89] A. Mangipinto, F. Lombardi, F. D. Sanvito, M. Pavičević, S. Quoilin, and E. Colombo. "Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries." In: *Applied Energy* 312 (2022), page 118676. DOI: 10.1016/j.apenergy.2022.118676.

[90] European Commission. *Ecodesign impact accounting annual report 2020 : overview and status report.* Technical report. Directorate-General for Energ, 2020. DOI: 10.2833/72143.

[91] European Commission. *COMMUNICATION FROM THE COMMISSION: Ecodesign and Energy Labelling Working Plan 2022-2024.* Technical report. 2022.

[92] Green Power Denmark. *Guide for grid connection of demand installations to the low-voltage grid.* Technical report. 2022, pages 1–42.

[93] G. Rampinelli, A. Krenzinger, and F. C. Romero. "Mathematical models for efficiency of inverters used in grid connected photovoltaic systems." In: *Renewable and Sustainable Energy Reviews* 34 (2014), pages 578–587.

[94] ENTSO-E. "Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area." In: (2022), page 65.

[95] A. Thingvad. "The Role of Electric Vehicles in Global Power Systems." PhD thesis. 2021.

[96] C. Ziras, L. Calearo, and M. Marinelli. "The effect of net metering methods on prosumer energy settlements." In: *Sustainable Energy, Grids and Networks* 27 (2021), page 100519.

[97] *Elspot price data.* https://www.nordpoolgroup.com/historical-market-data/.

[98] Radius Elnet A/S. "RADIUS 2021 Tariffs." In: (2021), pages 1–4.

[99] *Emission data.* https://www.energidataservice.dk/tso-electricity/co2emisprog.

[100] *Declaration emission per hour.* https://www.energidataservice.dk/tso-electricity/declarationemissionhour.

[101] D. M. Institut. *Vejrarkiv.* https://www.dmi.dk/vejrarkiv/manedens-sasonens-og-arets-vejr/tekst-kort-og-nogletal-maned/.

[102] L. Calearo, A. Thingvad, K. Suzuki, and M. Marinelli. "Grid loading due to EV charging profiles based on pseudo-real driving pattern and user behavior." In: *IEEE Transactions on Transportation Electrification* 5 (2019), pages 683–694.

[103] H. H. I. Ipsen, A. T. Thingvad, L. C. Calearo, and M. M. Marinelli. "Economic Value and User Remuneration for EV Based Distribution Grid Services." In: (2020).

[104] A. Thingvad, P. B. Andersen, T. Unterluggauer, C. Træholt, and M. Marinelli. "Electrification of personal vehicle travels in cities-Quantifying the public charging demand." In: *ETransportation* 9 (2021), page 100125.

[105] H. Lund and P. A. Østergaard. "Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation." In: *Energy* 25 (2000), pages 299–312.

PART II

Collection of papers

PAPER [P1]

Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspective

Authors:

Kristian Sevdari, Lisa Calearo, Peter Bach Andersen, Mattia Marinelli

Published in:

Renewable and Sustainable Energy Reviews

DOI:

10.1016/j.rser.2022.112666.

Renewable and Sustainable Energy Reviews 167 (2022) 112666

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives

Kristian Sevdari *, Lisa Calearo, Peter Bach Andersen, Mattia Marinelli

Division for Power and Energy Systems, Technical University of Denmark, Frederiksborgvej 399, Building 776, 4000 Roskilde, Denmark

ARTICLE INFO

Keywords:
Ancillary services
Flexibility services
Frequency services
Electric vehicles
Charging clusters
Smart chargers

ABSTRACT

The transformation towards a sustainable power system calls for new ways of operating the network. In that regard, electric vehicles (EVs) with their charging infrastructure qualify as a flexible resource. This paper interconnects ancillary services and EV flexibility to help system operators (SOs) and flexibility providers understand the role and localize EV-chargers in the power system. First, the focus is on SOs. The manuscript reviews ancillary services based on power system operational challenges. The ancillary services are differentiated between 8 frequency and 32 flexibility services. These are then subdivided depending on the management control: the first group includes inertia, primary, and secondary/tertiary frequency control, while the second includes congestion management, voltage regulation, power quality, grid stability, and emission management. Of all the different services, the ones that can be provided by EV-charger are highlighted and classified into 12 geo-electrical charging clusters. Second, the focus is moved to the flexibility providers. Independently from location, to provide ancillary services with EVs, multiple actors are recognized: the end-user, the charging site operator (CSO), the charging point operator (CPO), the aggregator, the energy community, the distribution system operator (DSO), and the transmission system operator (TSO). The collaboration between the actors is today carried out by making alliances, to help exchange knowledge and gain confidence in ancillary services provision. In conclusion, the literature review presents the characteristics of 27 slow (up to 50 kW) smart chargers, the common flexibility features being scheduling (100%), modulation (89%), and phase switching (10%).

1. Introduction

The conventional grid planning process requires the decision of the grid components capable of covering the maximum demand of the system and generally have a useful life between 25 and 50 years [1,2]. However, grid sizing and normal operation are challenged by the increasing penetration of intermittent renewable energy resources (RESs) and new distributed technologies [3]. For instance, the EVs rapid growth has an adverse instantaneous power delivery effect; the simultaneous charging can potentially harm the grid or require large grid upgrade investments [4,5]. Therefore, power system flexibility (PSF) is a possible solution to the sustainable power system paradigm [6]. For example, the authors of [7] highlight how PSF can substitute unnecessary grid upgrade or support the grid infrastructure. Fundamental work on flexibility in the power system has been presented in [8–14]. Authors agree when defining flexibility according to (i) type of flexibility resource (ii) duration and (iii) incentives for activation. In addition, authors of [15,16] emphasize the importance of relating flexibility with geographic granularity, system operators, and market interoperability. Thus, a flexibility solution is the combination of flexible resources, which can be further categorized on (i) demand, (ii) supply and (iii) grid-operation flexibility [8,10], with market enablers [11,12] on a predefined time and space domain [14,15]. Hence, highlighting the need for new markets, regulations, and codes of practices to harvest the flexibility value proposition. Furthermore, the authors of [17] define the flexibility value proposition on current markets and systems, while the authors of [18,19] suggest that the network can become more cost-effective by incorporating flexibility into the grid planning phase.

1.1. Motivation and research gap

The first step in a successful implementation of PSF is to agree on a definition of PSF. The authors of [6,9] have provided a historical background for the flexibility term used in the context of power systems and have underlined the lack of clarity in reviews of the literature. Our manuscript agrees with the PSF definition proposed by authors of [9],

* Corresponding author.
E-mail address: krisse@dtu.dk (K. Sevdari).

https://doi.org/10.1016/j.rser.2022.112666
Received 22 December 2021; Received in revised form 20 April 2022; Accepted 1 June 2022
Available online 20 June 2022

List of Abbreviations

AGC	Automatic generation control
BRP	Balancing responsible party
CPO	Charging point operator
CSO	Charging site operator
DER	Distributed energy resource
DSM	Demand side management
DSO	Distribution system operator
EV	Electric vehicle
FCR	Frequency containment reserve
FFR	Fast frequency reserve
FRR	Frequency restoration reserve
HAN	Home area network
OCPP	Open charge point protocol
PSF	Power system flexibility
RES	Renewable energy resource
RoCoF	Rate of change of frequency
RR	Replacement reserve
SO	System operator
ToU	Time of use
TSO	Transmission system operator
TyoU	Type of use
V1G	Unidirectional smart charger
V2G	Vehicle-to-grid

where PSF is strictly connected with the ancillary services and reads as follows:

"The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions".

The British PAS1879 code of practice [20] provides a standardized control for the power of domestic smart appliances subject to consumer consent. In Denmark, instead, the flexibility services procurement guidance [21] displays a market structure that exploits the current infrastructure for data management, monitoring, and validation. This guide, heavily based on the findings of the EcoGrid 2.0 research project [22], aims to stimulate DSOs to procure flexibility services instead of grid reinforcement without compromising their radial network N-1 spare operational capacity. Taking inspiration from such British and Danish initiatives, the rich PSF literature, and the integration of EVs in the power system [23,24], the entire process of delivering a flexibility solution should incorporate five principles:

1. Interoperability—consumers should have the possibility to choose from different flexibility providers [20,25].
2. Data privacy—personal data should be used under clear consent agreements and remain secured/encrypted on flexibility providers [11,12].
3. Cyber security—confidentiality and control services of smart appliances should never be breached by an unauthorized user [13, 26].
4. Grid stability—each flexibility service activation should not compromise grid stability and resilience [8,27].
5. Transparency and fairness—system operators and market enablers should provide standardized guidelines for all participating actors [21].

The study investigates the issue of grid stability and acknowledges the missing link between PSF and ancillary services. Previous review articles have a wide scope regarding flexibility assets [9,12] and flexibility actions such as demand side management (DSM) [16], energy efficiency and network reconfiguration [26,27], without looking at practical ancillary services. Others review market concepts [11,12]. A more narrow scope on flexibility assets is followed from [23,24], looking at EVs, probably the most influencing up-coming technology. However, authors of [23] are discussing a conceptual framework for EVs grid integration starting from technical to economical and regulatory aspects, without analyzing ancillary service provision. Further, authors of [24] look into ancillary services from EVs, but focusing on optimization techniques. Lastly, the lack of technical and geographical connection between ancillary services and EVs, is also highlighted in [28]. The manuscript analyzes such research gap with two major ancillary services subgroups: frequency and flexibility services. The distinction between the two is needed to investigate such services specifically for EVs.

1.2. Contributions

By looking at the power system operation challenges, first ancillary services are presented in this article. These are distinguished between frequency and flexibility services. Second, ancillary services that EVs can provide are presented. Third, the ancillary services are reflected in the charging clusters and charger technology available today. The objective of the article is to help SOs and flexibility providers better understand the role of the EV charger in the power system and what the EVs charger can and cannot do. The main contributions can be summarized as follows:

1. Frequency and flexibility service review with highlights of services delivered from EVs.
2. Distinction of geo-electrical charging clusters to identify where and what services from EVs can be offered.
3. Identification of EV flexibility alliances and stakeholders helping ancillary services provision.
4. Smart charger definition and review of 27 slow (up to 50 kW) smart chargers present in the market today.

The rest of the paper is structured as follows. Section 2 describes the paper methodology and the conducted review workflow. Further, Section 3 introduces frequency and flexibility services, which Section 4 utilizes to sketch the framework of the services. Section 5 classifies the current smart chargers' state-of-the-art technology and Section 6 concludes the article with the main findings.

2. Methodology

The methodology and workflow are presented in Fig. 1. The goal of the paper is to link ancillary services provision with electric vehicles. To do so, two parallel workflows are performed (Steps 1–4 and 5–9). Starting with the literature review, ancillary services (step one) and EV grid integration (step five) are the keywords used on the Google Scholar and IEEE Xplore search platforms. The introduction of the EU Electricity Market Directive (2019) [29], the British PAS1879 code of practice, and the Danish flexibility procurement guidance are important directives to gain confidence in ancillary services provisions. Hence, the ancillary services literature screening process (step two) benefits from the chosen eligibility criteria and limiting the scope to European ground. Similarly for the EV grid integration literature, the eligibility criteria (step six) is the charging behavior studies and notations followed from the IEA. On the one hand, ancillary services are classified on frequency and flexibility services (step three). On the other hand, charging behaviors are classified on the basis of charging locations as electrical and geographical charging clusters (step seven).

Step four analysis the ancillary services by highlighting services delivered from EVs. Additionally, based on market platforms proposed from demonstration projects, the paper recommends a flexibility supply

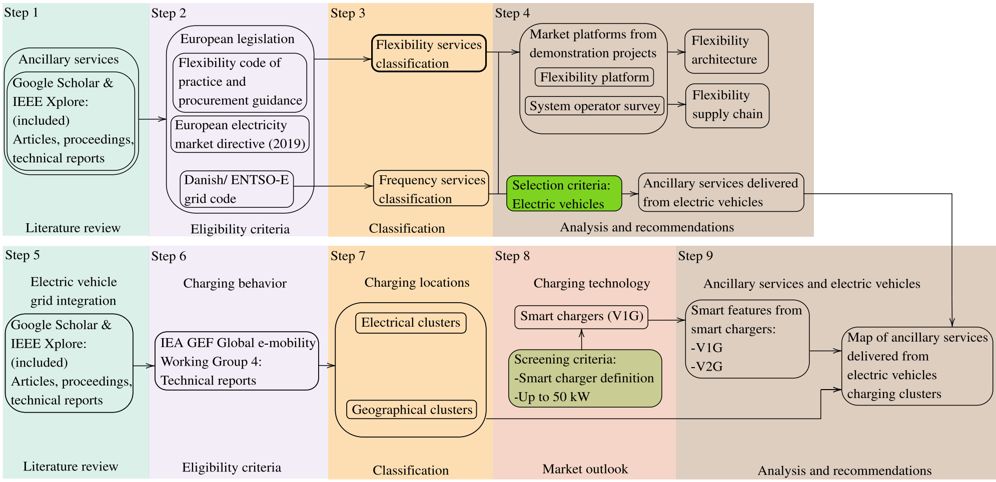


Fig. 1. Description of the methodology and the work-flow performed in this paper.

chain and architecture. Here, a recent market-based flexibility survey among Nordic DSOs [30] expected flexibility to have growing importance. However, Nordic DSOs lacked confidence in participating in or creating such markets. Furthermore, looking at European EVs market operators and research projects, we identify flexibility supply chain actors and the latest formed EV alliances.

In contrast, before analyzing the charging clusters (Fig. 1 step nine), the study conducts an European charging technology market outlook (step eight) based on a smart charger definition and charging power up to 50 kW. Such infrastructure is needed to link the charging clusters with the ability to provide ancillary services from EVs. Therefore, the last step sketches a map of potential ancillary services to be offered from the EVs charging clusters.

3. Ancillary services and electric vehicles grid integration

3.1. Electric vehicles potential

Authors of [31] quantify the demand response flexibility potential for two European system scenarios. By 2050, there is a flexibility potential from EVs of 878 out of 1648 GW for the centralized system scenario and 260.7 out of 370 GW for the decentralized system scenario. Thus, by acknowledging even the large potential of economical savings from smart charging [23,32], this article focuses on EVs charging operation. Flexibility from EV and charging station is dependent on user constraints, time availability, charging location, etc. [33]. In particular, the residential and workplace charging environment top the parking period, while it remains dominated by slow charging, commonly below 50 kW charging power [34]. To perform EV ancillary services, a smart charger (unidirectional (V1G) or bidirectional (V2G)) is required [23,35]. Unidirectional smart chargers (V1Gs) can only draw power from the grid, while vehicle-to-grid (V2G) chargers can also inject power to the grid. This study focuses on V1Gs, which are reviewed in Section 5. The V2G technology, previously discussed in [23,36], will become more attractive when future vehicles are equipped with on-board bidirectional chargers, or the price of V2G chargers decreases significantly [37].

Further, the recent update on the Danish grid code has included the V2G technology part of the same group with battery energy storage [38]. Depending on the storage size (kWh), different groups are present in the Danish grid code. These different groups mandate which ancillary services should the V2G technology provide. To the authors' knowledge, ancillary services from EVs have been discussed in the literature without a full comprehension of all services. On top of that, the literature is missing a geographical localization of ancillary services from EVs.

3.2. Ancillary services

Under the new sustainable power sector paradigm, the operational needs of the power system can be grouped into three pillars: (i) Adequacy and security of supply (having enough generation to cover peak demand at any time) [39], (ii) Power system stability (the ability of the power system to regain the operating equilibrium state after experiencing a physical disturbance, for a given initial state without violating system variables, hence the system remaining intact) [40,41], and (iii) Power system resilience (ability of the system to react to extreme, or catastrophic events) [42]. The conventional way to cover such requirements is through grid codes, wholesale/retail energy markets and ancillary services markets, more specifically balancing markets [43,44]. However, these services have limitations on the upcoming decentralized grid, because they were initially developed for the centralized one [45]. Therefore, extensive research is conducted on complementary services [46,47]. The entirety of the services required from the power system perspective falls under ancillary services [48]. Those account for all services offered in the balancing and flexibility markets. Frequency services maintain the system-wide frequency characteristic, while the flexibility services assist local challenges.

3.3. Frequency services

The conventional method for controlling the system frequency depends on inertia, primary, secondary, and tertiary frequency control [44]. This section describes the frequency stability and services first, and then it highlights the services that can be delivered by EVs.

3.3.1. Frequency stability conundrum

First, the integration of converter-based generation, phase-out of thermal units lead to the reduction of system inertia [49,50]. The system inertia and rotating load-damping effect are further challenged by the growth of high voltage direct current connections [51] and the uptake of load frequency drivers [52], respectively. Second, the increased penetration of RESs and the phase-out campaigns of polluting thermal units reduce the number of generators able to provide reserve

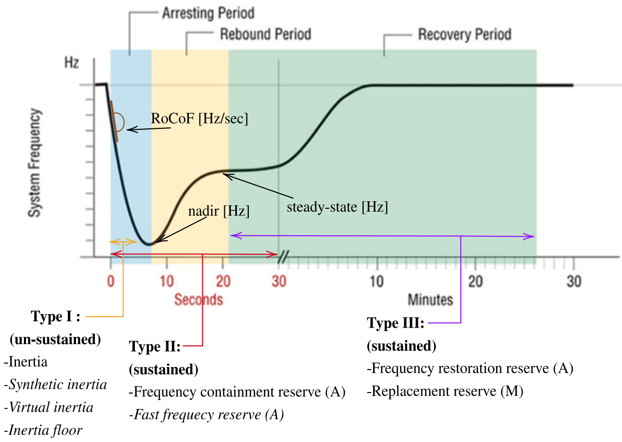


Fig. 2. Frequency services timeline extended from [47,60,65]. The service in *italic* describes novel services. "A" is automatic activation, while "M" is manual activation.

power for primary (containment reserve) and secondary (restoration reserve) frequency control [53]. On top of that, the frequency stability is threatened by both the loss event of generating units [40] and the ill generation forecast of RESs [48]. Hence, due to the low-inertia in the system, even mild disturbances would cause a large enough rate of change of frequency (RoCoF) to activate defense plans [54], such as under/over-frequency schemes [55]. In addition, a large RoCoF can activate protection relays, resulting in cascaded trips and leading to system collapse [56]. Acknowledging such challenges, the Nordic TSOs have proposed three low-inertia mitigation measures [57,58]: (i) restricting the dimensioning incident; (ii) assessing the minimum systems' inertia; and (iii) dispatching faster active power reserves that supplement the primary frequency control. Such measures also address the participation of converter-connected RESs in frequency services [59–61]. Similarly recommendations are followed-up in North America [62,63], Australia, United Kingdom [53,64], and Ireland [53,65]. These measures try to arrest RoCoF, avoid a low frequency nadir, and help the system land at a desired steady-state frequency, which is affected by the size of the contingency, systems' inertia [66], speed, and magnitude of injected active power response from generators [62].

3.3.2. Conventional and novel frequency services

Fig. 2 describes frequency regulation services by timeline and distinguishes between conventional and novel services (supporting a low-inertia system). Frequency services are divided into activation periods and service types. The periods are the arresting, rebound, and recovery period [60], while the types are I (un-sustained), II (sustained), and III (sustained) [53,67]. The nomenclature in Fig. 2 is adopted from ENTSO-E [68].

After a mismatch between production and consumption, a sharp increase/decrease of the frequency is experienced. Here, the frequency-arresting period is the most critical. Multiple varieties of the system inertia are automatically and instantaneously activated. However, such measures are not sustained, hence, those are complemented by the governor/droop-based control of frequency containment reserves (FCRs), and the novel fast frequency reserves (FFRs). The latter one does not intend to replace FCRs rather support them [57]. From the observed implementations and their respective requirements, two FFRs activation approaches exist. Nordic TSOs and ERCOT are dispatching FFRs after the FCRs [63,69], while EirGrid and NG ESO are dispatching the FFRs before the FCRs [65,70]. Another difference is the hard constraints of delivering FFRs. The NG ESO and ERCOT require full delivery below 1 s, while EirGrid and Nordics TSOs require full delivery below 2 s. On the one hand, this hard time constraint is a reason that conventional steam and hydro turbines are unable or do not desire to participate in such reserves [58]. On the other hand, converter-connected resources and frequency-responsive demand response cope well with such constraints, and those might dominate the FFRs [58].

After experiencing the minimum frequency (frequency nadir), there is the rebound period, which goal is to land the frequency in a steady-state. The amount of time and the frequency deviation from the nominal value are subject to the speed and the magnitude of injected power response (type II reserves) [68]. After reaching the frequency steady-state, the power system requires automatic generation control (AGC) to clear the frequency deviation by activating frequency restoration reserves (FRRs). Hereafter, the system is entering the recovery period where the frequency should adhere towards the normal operation. Once the AGC is provoked, the type II reserves are automatically deactivated. Further, the replacement reserves (RRs) replace the FRRs, and the FRRs can be restored for a new event [67].

Frequency control techniques are out of the scope of this paper, however, for a detailed review it is recommended to refer to: (i) photovoltaics [85,86]; (ii) wind [67,86]; (iii) battery energy storage system [47,76] and (iv) different energy resources [62,87]. The characterization of the frequency services depending on the type is presented in Table 1. This characterization per type is based on three reasons: (i) the goal of the service (reduce RoCoF, delay and prevent critical frequency nadir, clear frequency deviation), (ii) the stretch on the frequency excursion period (arrest, rebound, and recovery period) and (iii) the activation topology (RoCoF or frequency-based). The table summarizes the services presenting type and criteria. According to ENTSO-E, frequency service providers can be generators or loads [88]. The table also highlights in bold and * the five services that can be provided by EVs and their V1G or V2G chargers. Examples of how frequency services can be provided are as follows: (i) phase-locked loop (PLL) to measure RoCoF and a proportional-based control deploys synthetic inertia [89], (ii) virtual synchronous machine [90], and virtual oscillator control [91] methods to deploy virtual inertia from grid forming inverters [92], (iii) droop-based control for deploying FFR, or FCR [78], and (iv) the AGC which is a proportional integral-based control for deploying FRR or RR [82].

These services have already been validated in research; however, fast delivery services such as synthetic inertia, virtual inertia, and FFR are not commercially available. The main reason for this is the requirement to deliver such services with response time below 1 s. Of the rest of commercially proven services, due to economic feasibility, only FCR is applied in the field, i.e., droop-based control in Denmark [78]. FRR and RR have only been applied in pilot projects. The

Table 1
Frequency services classification. * marks services that can be delivered from EVs via **uni/bi-directional smart chargers (V1G and V2G)**, or only *bidirectional chargers (V2G)*.

Type	Explanation	Design stage
Type I: un-sustained *Arrest period* *RoCoF-based activation*	Goal: Should reduce the RoCoF (prevent triggering RoCoF relays) and delay the frequency nadir.	
1. Inertia [59,61,71]	1. Natural feature of rotating generators from which benefits the frequency stability.	1. -
2. Synthetic inertia* [72–75]	2. Capability of converters to try reducing RoCoF by injecting power into the system. Also known to be related to grid following converters.	2. Research proven
*3. Virtual inertia** [74,76]	3. Capability of converters to try reducing or improving RoCoF by injecting power into the system. Also known to be related to grid forming converters.	3. Research proven
4. Inertia floor [59,72,77]	4. Requesting rotating inertia to maintain or improve optimal system's inertia, which mitigates frequency excursions.	4. -
Type II: sustained *Arrest-rebound-recovery period* *Frequency-based activation*	Goal: Should arrest the frequency excursion by preventing a critical frequency nadir that can trigger defence schemes.	
5. Fast frequency reserve* [58,78]	5. Requesting a power injection with a very fast delivery period, typically less than 2 s, to be maintained for a predefined time span accordingly to the grid-code.	5. Research proven
6. Frequency containment reserve* [79,80]	6. Requesting a power injection with a fast delivery period, typically less than 15 sec, to be maintained for a predefined time span accordingly to the grid-code.	6. Research proven Commercial proven
Type III: sustained *Recovery period* *Frequency-based activation*	Goal: Should replace the generation loss and restore normal operation.	
7. Frequency restoration reserve* [81,82]	7. Requesting a power delivery to restore the frequency deviation to the nominal operating point.	7. Research proven Commercial proven
8. Replacement reserve* [83,84]	8. Requesting a power delivery (generator rescheduling) to fully clear the frequency deviation.	8. Research proven Commercial proven

increase penetration of EVs can mature (reduce the cost) the charging technology, and the rising electricity spot-prices could make FRR and RR economically viable very soon.

3.4. Flexibility services

Frequency regulation is a system-wide characteristic that cannot be contained locally. On the contrary, flexibility services reflect a local problem. Thus, flexibility services are, among others, linked to reactive power support, congestion management, power quality, power smoothing, and post-fault restoration services [93].

3.4.1. Flexibility services definition

Moving forward, this study lists the flexibility services that can be provided from EVs. While for frequency services there is an available market framework [94], the flexibility services are lacking, or rather are on the first steps of the implementation of such markets. For example, the authors of [95] discuss how flexibility products can be delivered, as ramp or energy, whereas in [6] a capacity allocation product is discussed. Recalling from the aforementioned literature [9,24], they agree on the allocation of flexibility services based on five features: resource type, duration, incentives, location, and enablers. Therefore, the authors propose the following definition for flexibility services:

Flexibility service refers to scheduling and/or modulation of the collective/single consumption or generation of electrical appliances or distributed technologies, in agreement with the costumer (consumer or generator) or mandated in the grid code, after responding to signals from market enablers, to increase network reliability and efficiency on a predefined time and location.

3.4.2. Flexibility services classification

Based on the aforementioned pillars of power systems operational needs and on the Danish flexibility services procurement guidance, this paper characterizes the flexibility services into three categories: natural, scheduled, and conditional. Natural flexibility services refer to actions actively enabled by the SO without the need for a procurement process, namely demand response programs, control of network components and grid code requirements. Scheduled services account for measures procured by the SOs to not jeopardize system safety operation or counteract N-1 situations. Conditional flexibility services are activated to restore system stability or increase power system efficiency. The difference between conditional and scheduled services is the activation type. For conditional services the activation is post-event, whereas for scheduled services it is a pre-event or during event activation. Natural flexibility comes first, it is a tool only based on the agreement with the user, and it potentially reaches the highest number of flexibility providers, along the timeline. If natural flexibility is not enough, scheduled flexibility is used by SO in a dedicated area, with a specific timeline and fewer providers. Similarly, conditional flexibility is the last resource to avoid further escalation of the problem or help the system recover. In addition, what may sound important to the reader are the steps SO takes to acquire flexibility services (Table 2 and Figs. A.8, A.9): first, exhaust the available (natural) services and then use the market ones (scheduled or conditional). Table 2 categorizes the flexibility services by type – natural, scheduled, and conditional –, by area DSO or TSO and by topic. Also, the table gives a short description of the services and highlights the services that can be delivered by EVs by bold style and *. Here, 26 and 20 out of 32 flexibility services can be delivered via V2G and V1G, respectively. The extra services that can be provided through V2G refer to the possibility of injecting power into the grid and providing reactive power support.

Further, the V1G can deliver flexibility services via scheduling or modulating the charging process. These features are fully investigated

Table 2
Flexibility services classification based on type, enabler and grid location. * marks services that can be delivered from EVs via both **unidirectional and bidirectional smart chargers (V1G and V2G)**, or only *bidirectional chargers (V2G)*.

Type	DSO area	Explanation	TSO area	Explanation
Natural and w/o procurement	Congestion management (DSO) via non-dispatachable demand response programs such as [96–100]: **1. Time of Use (ToU)*** **2. Dynamic pricing (DP)*** **3. Critical peak pricing (CPP)*** **4. Peak-time rebate (PTR)*** **5. Extreme day pricing (EDP)*** **6. Inclining block rate (IBR)*** **7. Peak upgrade***	It provides an economic incentive for consumers to reduce their consumption. 1. Putting an extra flat fee on particular hours. 2. Putting an extra dynamic fee. 3. Putting an extra fee on energy used during peak time. 4. Offering payments for those who reduce consumption during peak time. 5. Increasing DSO fees on a high loading day. 6. Increasing the electricity price rate with the end-user consumption rate. 7. Proposing an end-user peak value and peak time-span (forcing an infrastructure upgrade if the time spent on the peak is met).	Emission management [101]: **1. Type of Use (TyoU)***	It intends to reduce consumption from polluting generators. 1. Inducing an extra fee related to grid carbon intensity.
	Congestion management (DSO) via network components [102,103]: 8. Network reconfiguration	8. Remote control of radial networks components to better manage their loading.		
	Grid stability (DSO) via network components [104–106]: *1. Low-voltage ride through** *3. Fault ride through** *3. Power factor control (TSO)** *4. Anti-islanding**	It mandates capability features from the grid code to assist system stability. 1. Requesting to withstand a low-voltage event in the network (high Q consumption nearby). 2. Requesting to withstand a voltage-dip (grid fault) for a defined time, as stated in the grid code. 3. Requesting reactive power control proportionately (determined by the droop) to active power in the point of connection. 4. Requesting from grid connected inverters to be able to recognize islanding events and prevent them.	Grid stability (TSO) via network components [38,105]: *1. Low-voltage ride through** *2. Fault ride through ** *3. Power factor control (TSO)** *4. Anti-islanding**	It mandates capability features from the grid code to assist system stability. 1. Requesting to withstand a low-voltage event in the network (high Q consumption nearby). 2. Requesting to withstand a voltage-dip (grid fault) for a defined time, as stated in the grid code. 3. Requesting reactive power control proportionately (determined by the droop) to active power in the point of connection. 4. Requesting from grid connected inverters to be able to recognize islanding events and prevent it.
	Voltage regulation (DSO) via network components [103,107]: 1. Tap-changers 2. Static VAr compensators	It tackles voltage unbalances, under and over-voltage challenges. 1. Remote control of transformers tap-changer to help tackle voltage stability. 2. Remote control of reactive compensator to mitigate voltage unbalanced networks.	Voltage regulation (TSO) via network components [108–110]: 1. FACTS *2. Reactive power support**	It tackles under and over-voltage network challenges. 1. Remote control of power electronic devices located in substations to maintain voltage stability. 2. Requesting reactive power support for weak grids. Capability curves are mandated in the grid code.
Scheduled and subject to procurement	Congestion management (DSO) [111,112]: **9. Valley-filling (DSO)***	It demands a load curtailment or induced power to reduce loading stress on network components. 9. Requesting a load shift in time from the consumers.	Congestion management (TSO) [113]: **1. Valley-filling (TSO)***	It dictates a load reduction or induced power to manage high-voltage network loading. 1. Requesting a load shift or delay in time from the consumers.
	Voltage regulation (DSO) [114,115]: **3. Under/over voltage regulation***	3. Requesting active or reactive power support for under and over-voltage networks.		

(*continued on next page*)

in Section 5. Five major topics are recognized: congestion management, voltage regulation, power quality, grid stability, and emission (CO2) management.

Congestion management refers to measures taken from SO to maintain the desired loading on their network components, such as transformers and electric lines. The reasons for doing so are twofold: (i) high overloading of a grid component will instantly damage the component [135] and (ii) moderate overloading will produce heat higher than normal from the current flowing through the device. With time, extra heat shortens the lifetime of the device, requiring earlier maintenance [136]. In Appendix A a Danish city distribution network [137] named Frederiksberg is taken as example to present the provision of congestion management.

Voltage regulation refers to measures taken from SO to maintain voltage stability and overcome short-circuit scenarios. Here, the paper distinguishes between voltage and reactive power support. In the former, both active and reactive power play a role, while the latter is more related to reactive power support with a focus on weak grids [138]. The cause of voltage instability derives from the fact that the power network

Table 2 (*continued*).

Type	DSO area	Explanation	TSO area	Explanation
Conditional and subject to procurement	Power quality [116–119]: **1. DER power-smoothing*** *2. Damping harmonics** *3. Power factor control**	It tackles grid losses and improving supply quality: 1. Mitigate power flickering effects from the highly volatile nature of renewable sources. 2. Requesting to filter the harmonics via filters or inverters. 3. Requesting to correct the power factor of a customer (capacitive or inductive).	Grid stability (TSO) [120–125]: **1. RES power smoothing*** *2. Emergency power** *3. Black start capability** **4. Energy arbitrage*** 5. Seasonal balancing *	It tries to improve or backup the network's power stability. 1. Requesting to smooth power variations from RES. 2. Requesting to energize critical infrastructure during emergencies. 3. Requesting to generate active power to energize lines or start-up larger power plants. 4. Requesting to fill the mismatch absent from BRP commitment, by reducing the load. 5. Requesting to store large renewable energy surplus and deliver it back on low renewable season production.
	Voltage regulation (DSO) [126–128]: **4. Voltage unbalance mitigation*** *5. Reactive power support**	4. Requesting to alleviate voltage asymmetries by better balancing the phase loading. 5. Requesting reactive power support for weak grids.		
	Grid stability (DSO) [129,130]: *3. Intentional islanding** *4. Emergency power (DSO)**	3. Requesting to maintain frequency/voltage stability after the isolation of a part of the grid . 4. Requesting to energize local loads during emergencies.		
	Congestion management (DSO) [112,131,132]: **10. Peak-shaving (DSO)*** **11. DER power matching*** **12. Phase balancing***	10. Requesting a load reduction or maintaining a predefined load baseline during peak time. 11. Requesting to absorb surplus renewable energy production to prevent negative power flow congestion (from 5-min to a couple of hours). 12. Requesting a transfer of the load to less loaded phases.	Congestion management (TSO) [133,134]: **2. Peak shaving (TSO)*** **3. RES power matching***	2. Requesting a load decrease or sustaining a predefined load baseline during peak time. 3. Requesting to absorb excess renewable energy production.

is operated close to stability limits and different load characteristics trigger it [139]. In Appendix A the provision of voltage regulation is illustrated from the perspective of DSO.

Power quality refers to the measures taken from DSO to improve supply quality and reduce grid operational losses. Here, the voltage regulation service is distinguished from the power quality service because it belongs to both DSO and TSO. In contrast, the latter belongs to the DSO. Besides, voltage regulation itself has become quite important; hence, it deserves to be mentioned separately. Power quality is focused on the fast dynamics of switching of electronic devices [140], the mitigation of distributed energy resources (DERs) power flickers [116,121], and the control of the end-user power factor [141].

Grid stability services cover the power system stability, adequacy, and security of supply outside of the wholesale electricity and balancing markets and are operated by DSO and TSO. Services such as low-voltage/fault ride through, power factor control and anti-islanding are generally capabilities mandated in the grid code. In a high integration scenario of RESs, RESs power smoothing services might be required to operate the system safely and preserve frequency power reserves [121]. Similarly, energy arbitrage and seasonal balancing are believed to be necessary services to cope with the unpredictability of RESs [142, 143]. Additionally, emergency power and black-start capability are programmed for blackouts (according to ENTSO-E) [144], or to provide emergency power to areas affected by local emergencies [130].

As the name suggests, *emission management* relates to a demand response service type of use (TyoU) that intends to avoid RESs spilling and reduce consumption from polluting generators. The TyoU induces fees for the carbon intensity depending on the generation mix. Higher fees correlate with high polluting generators.

Flexibility services are provided in the active and reactive power domains. For both domains, Table 2 noted flexibility services that are, on a dominant majority, at least research proven. Acknowledging the recommendations from [30] and the novel applications of commercial flexibility [20,21], stakeholders are only looking at active power services, mainly congestion management (refer to Table 2). In the short term, possible commercial flexibility services are demand response programs, TyoU, valley-filling and peak-shaving actions. In the long term, with large penetrations of EVs other flexibility services such as phase-balancing, power matching, and voltage regulation actions could be required.

4. Flexibility framework

4.1. Flexibility architecture and clustering

Another important step towards full activation of flexibility markets is the design of flexibility market platforms [145]. This has been researched and demonstrated through pioneer projects such as Piclo, Enera, Flex, GOPACS, NODES [30,146] and EcoGrid 2.0 [22]. The goal of such platforms is to couple flexibility providers with buyers of flexibility. Buyers of flexibility are SOs and providers of flexibility are aggregators or energy communities. Such aggregating entities utilize in an agreement the end-costumer flexibility (flexibility resource) and provide a flexibility offer to the flexibility platform. The flexibility platform decides for the winning bids. Taking advantage of the learning from these projects a stylized illustration of such platforms is displayed in Fig. 3.

4.1.1. Clustering

One important step before matching the flexibility services is clustering the EV owners based on their charging behavior. The results can be biased to early movers [147] as the industry is still in the early stages. However, by looking at different databases and clustering investigations, in Figs. 4 and 5(a), we first cluster according to the grid connection (low, medium or high-voltage) [148] and second based on the charging behavior. Here, a complete picture of the available

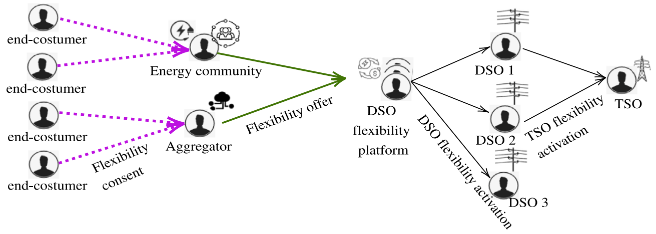


Fig. 3. Converged proposal for the DSO flexibility platform.

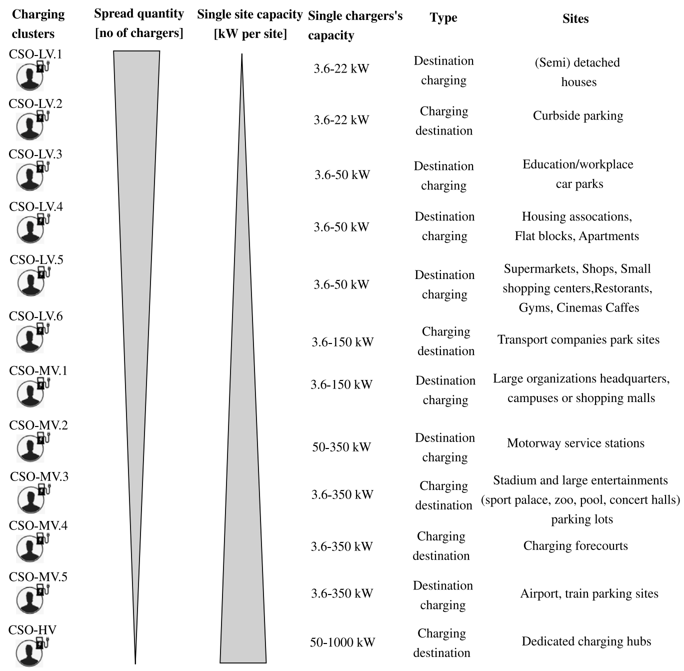


Fig. 4. The CSOs site characteristics. The column "type" extends from [154].

charging data sets can be found in [149], while for charging behavior, it is recommended [150,151], and for infrastructure deployment, it is recommended [152,153].

The literature review distinguishes between destination charging and charging destination. In the first, charging is complementary to other user needs, such as going to the supermarket, in the second charging drives the choice of the user needs. Furthermore, charging behaviors are reflected at different charging sites: (i) home [155,156] and public residential charging [157,158]; (ii) curbside [159–161] and semi-public charging [162,163]; (iii) workplace charging [164]; (iv) fleet charging [165]; (v) large semi-public charging [166]; (vi) fast(en route) charging [167,168]; (vii) special semi-public charging [169,170]; (viii) charging forecourts [171,172]; (ix) semi-private charging [173] and (x) charging hubs [174]. Although it is still quite early for the clusters to mature, the charging clusters derived from the review are in line with the clusters used in the Working Group 4 of the IEA GEF Global e-mobility program [175,176].

Accordingly, Fig. 4 illustrates with examples the CSO, which is the representative of the cluster. The CSO can incorporate one charger, in the case of a home charger or include multiple chargers such as the charging forecourts. The higher the site hierarchy, the fewer chargers there are, while the site connection capacity increases. Furthermore, it is a challenging task to estimate the number of chargers in each cluster. This factor is one of the current limitations on forecasting flexibility of charging clusters. In addition, the charging technology needs to be mature before trying any estimation. For example, most slow chargers today are single outlet; however, to increase utilization efficiency, dual outlet options are investigated. After identifying the charging clusters or CSOs, Fig. 5(a) matches the charging clusters with their grid location (low/medium/high voltage). Besides, it couples CSOs with possible delivery of flexibility and frequency services. This is achieved by matching the previously discussed ancillary services depending on V1G or V2G. The V1G represents a smart load, while V2G (converter technology) is similar to the battery energy storage. Further, the drawing in Fig. 5(a) pairs each CSOs with the charging technology (AC and DC smart chargers) and with different EVs ownership types (passenger cars, taxis and fleets, autonomous vehicles, shuttles, and public transport buses) [175,176].

4.1.2. Flexibility architecture

Based on the generalized flexibility architecture and clustering above displayed (Fig. 3), in this subsection we intend to provide an

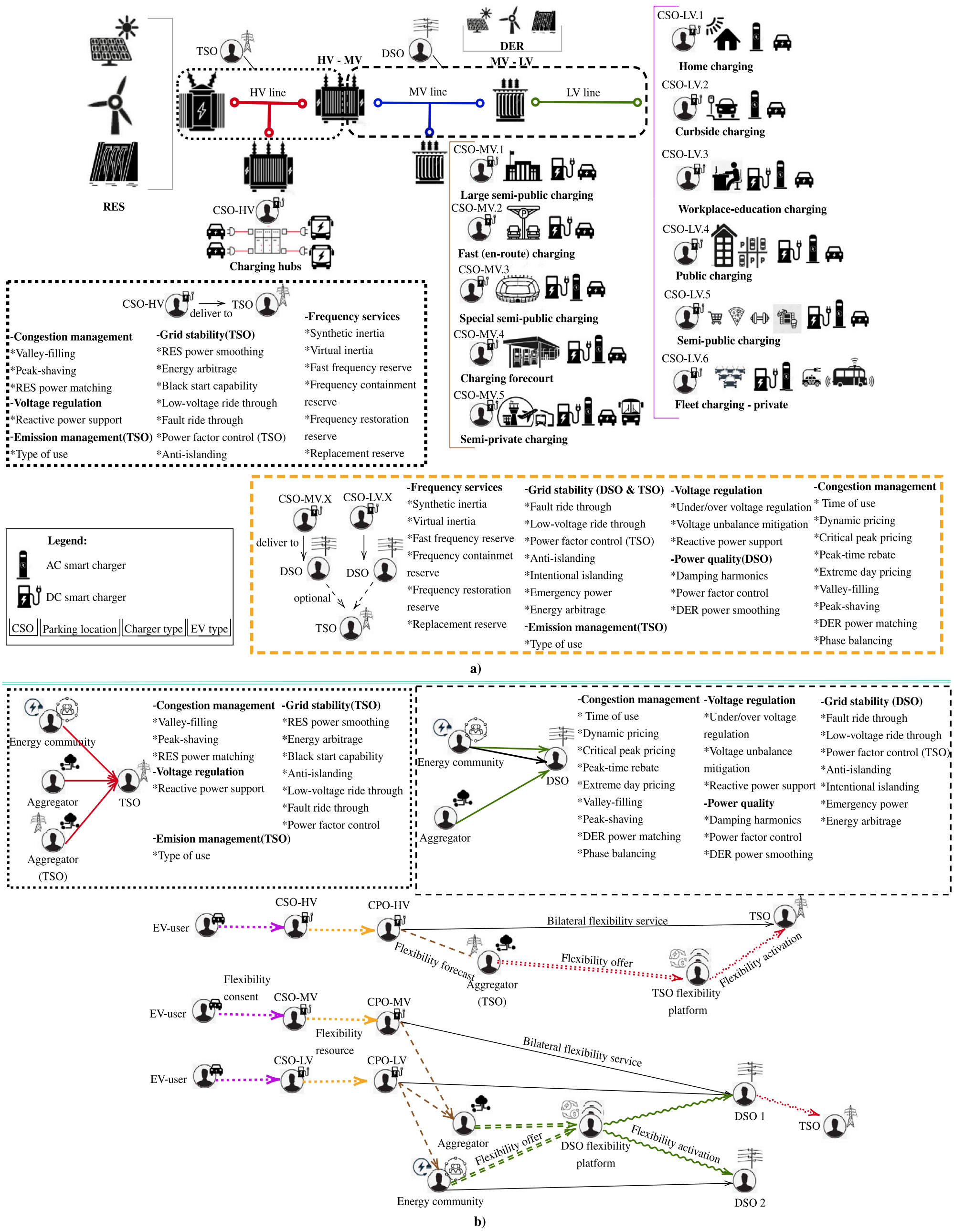


Fig. 5. (a) Geo-electrical clustering of frequency and flexibility services. (b) Flexibility services architecture.

overview for the EV flexibility architecture. Fig. 5(b) displays the flexibility architecture with all stakeholders, namely the EV-user, the CSO, the CPO, the aggregator, the energy community, the DSO, the TSO, and the flexibility platform. The EV-user provides consent of using its flexibility to the CSO [156]. The CSO is the first flexibility provider. Furthermore, the CSOs require an infrastructure to operate, namely the EV charger. The CSOs are supplied from charger manufacturers and can operate the infrastructure on their own or delegate it to someone else. Here, the CPOs concept is introduced, which can control (back-end control) the charging infrastructure. Further, it is recently observed alliances between CPOs and charger manufacturers. Hence, these alliances are made to offer a complete charging infrastructure package to the end-users and CSOs. A CPO can fully control one or multiple CSOs accordingly to the CSO desires. On the one hand, the CPO can deliver bilateral flexibility service to the SO. On the other hand, CPO can delegate front-end control (API interface) to an aggregator [177] or an energy community to participate in the flexibility market [178]. In this case, a larger entity is created, and CPO can help the process by providing flexibility forecasts of their sites to the aggregator or energy communities. Subsequently, the aggregator or energy communities bid a flexibility offer in the flexibility platform related to the DSOs or TSO network. The platform decides the winning bids and activates the flexibility service. Lastly, in Fig. 5(b) a summary of flexibility services from the aggregating entity is presented. Further, a novel aggregator-free approach is investigated from Danish ACDC and FUSE research projects [179,180]. Both projects investigate the bilateral flexibility services CPO-DSO.

4.2. Electric vehicles flexibility alliances

To participate in electricity markets an entity must become a balancing responsible party (BRP) and fulfill size, market, and grid requirements. Barriers such as size and market requirements can be overcome by forming alliances between SOs, and CPOs. To recall from above, CPOs are already forming alliances with charger manufacturers. Thus, different stakeholders are bypassing such barriers by offering full charging services package that include charging infrastructure and smart charging incentives (among others, smart charging is comprised of flexibility and frequency services).

Fig. 6 illustrates the supply chain of flexibility services provided by EVs, including examples from the Nordic countries. CPO can offer a bilateral flexibility service to SO, with the consent of CSO through centralized or distributed control of smart chargers [181]. A typical example is Powerloop, a project implemented in the United Kingdom between Wallbox, Octopus EV, and UK Power Networks [182]. Wallbox supplies a V2G technology to Octopus EV (the commercial name of the charger is Quasar). Octopus EV provides congestion management services to UK Power Networks (DSO) in agreement with end users. Similarly, the FUSE research project aims to combine Zaptec, Spirii, and Radius to simplify the development of flexibility services [180]. Zaptec supplies a state-of-the-art V1G to Spirii, which is the CPO. Spirii offers to its customers the possibility to participate in congestion management services. Radius, a Danish DSO will utilize the Spirii infrastructure to their benefits. Additionally, a more ambitious aggregator and CPO-free path is followed from the ACDC project [179]. The project aims to deliver an autonomously controlled distributed smart charger. The charger developed from Circle consult couples the DSO (TREFOR El-Net Øst) directly to the CSOs.

5. Smart chargers

After considering what services SOs require to maintain fully operational grids and highlighting which services can be delivered from the EVs charging cluster, this section reviews the slow smart charger technology. The charging infrastructure plays a central role in supporting EV adoption, and smart chargers are a promising distributed infrastructure coupling power system with the transport sector [143]. Therefore, first, we provide a definition for the smart charger, which will facilitate the correlation between ancillary services and EVs. Second, we review the current state-of-the-art of slow smart charger technology.

5.1. Dumb and smart charger comparison

International charging standards are well covered in the literature [35,36]. In this paper we focus on IEC 61851 [183], and based on it we define the differences between a dumb and a smart charger, as shown in Fig. 7. A *dumb charger* is a device comprised of circuit breakers, relays, and voltage oscillator, which maintains a constant control pilot duty cycle to charge the EV. The scheduling devices outside the dumb charger (on the grid and EV side) can turn on or off charging process. In addition, it illustrates a smart behavior from the user side, even though users own a dumb charger.

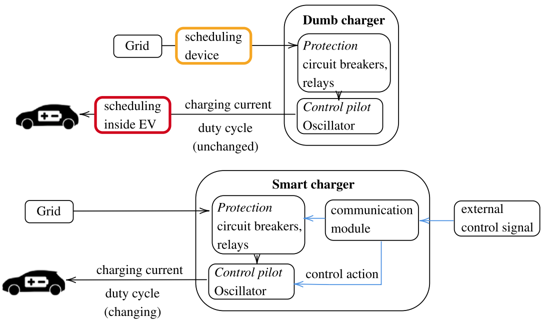


Fig. 7. Smart charger and dumb charger comparison.

A *smart charger* contains a communication module and can control the control pilot duty cycle, thus modulating or scheduling the charging

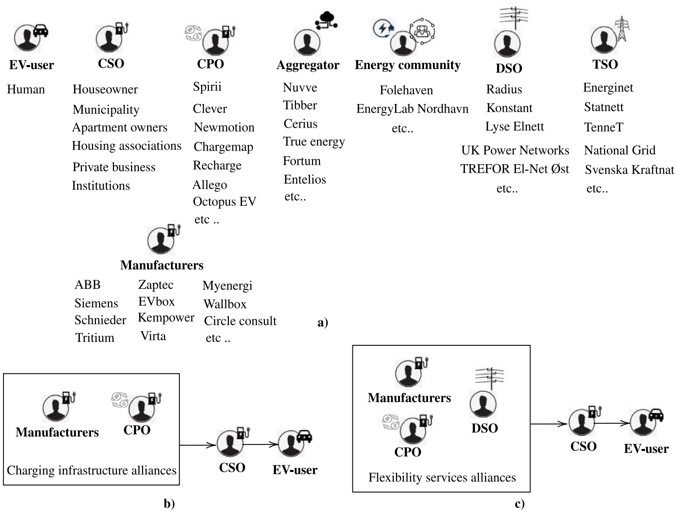


Fig. 6. (a) The EVs flexibility supply chain. (b) Charging infrastructure alliances. (c) Flexibility services alliances. Examples are provided for the Nordic countries cases.

process. Scheduling refers to turning on–off the charging process. Modulating refers to controlling the charging current through the control pilot. An optional action of smart chargers is the ability to control the open-closure of the relays, which allows a three-phase capable EV to perform a switch from three-to-one phase charging [184], hence, curtailing two of the phases. Here, it should be underlined that those chargers which can control their relays also offer the 0 Amp current option. This means that they can keep the EV on-board charger awake without drawing any current for the charging process.

Therefore, *a smart charger is a device providing protection, communication, at least scheduling and at most modulation and phase curtailment (3 to 1-phase switch) for the EV charging process*.

5.2. Control architecture

The control approaches of smart chargers can be divided into centralized, decentralized, and distributed. Table 3 merges the findings from authors of [5,185–189] regarding advantages and drawbacks of each control approach. So far, smart chargers have followed in a large majority the centralized control approach, mainly due to simplicity of implementation and a more mature architecture [190]. Besides that, recent initiatives are exploiting the distributed control approach [181, 191]. The main difference is the location of the intelligence. In the centralized case, the intelligence resides on the cloud, while in the distributed one, it is spread among the cloud and the virtual aggregator (local intelligence).

5.3. Flexibility services and smart chargers

EVs can benefit the power system providing as a large flexible energy resource. Nevertheless, such services are one side of the charging process decision-making. The other side relies on infrastructure owner's economic benefits and user's comfort. The authors of [192] highlight the EV multi-use or optimal designed strategies that combine different value streams for EVs. Here we argue the difference between flexibility services and smart charging strategies. The charging process can be scheduled or modulated. Smart chargers can offer both scheduling and modulation, while dumb chargers can provide scheduling via external interference.

Smart charging strategies aim at increasing consumer acceptance and satisfaction rate. Further, coordination is required to deliver a smart charging strategy. Examples of strategies are (i) scheduling-based control, the simplest smart charging strategy that can be performed from both dumb (with external help) and smart chargers [193], and (ii) modulation-based control, the exclusive feature of smart chargers. Smart charging strategies combine technical grid requirements with the economical benefits of owners and user comfort. Other examples of such strategies can be found in [192,194].

As discussed previously in Section 3, flexibility services aim to increase the reliability and efficiency of the grid. Flexibility services are key elements for designing smart-charging strategies that are beneficial for the power system and can be enabled from SO. Examples of such strategies comprising only flexibility services can be found in [195,196]. This means that smart-charging strategies can: (i) be beneficial to the grid or not and (ii) involve different flexibility services or none at all. Here, it is relevant to underline the importance of designing well-thought strategies due to the risk of causing grid avalanche effects [197]. For example, a smart charging strategy synchronized only with electricity spot prices can result in overloading of grid components [133]. Therefore, to limit the potential danger, the smart-charging strategies development should include more variables and account for possible rebound effects [198,199]. One example is the bill optimization strategy for a residential consumer, which can comprise of stacked services such as spot-price, time of use (ToU), avoid peak upgrade, offer valley-filling (DSO) and TyoU among others.

5.4. Smart chargers state-of-the-art overview

Smart charger technology is crucial for scaling up the charging infrastructure. To the authors knowledge a review of available smart chargers in the market is missing in the literature. In [200,201] the authors investigated the incompatibility of EVs chargers on a large scale. This study focuses on slow smart chargers, and it offers, for the first time, a market technological overview of 27 smart chargers. Based on [190], Tables B.1 and B.2 present a full picture of the current smart-chargers state-of-the-art technology up to 50 kW, which have controllable features. These will be referred to as "slow smart chargers" in the following. Smart charger characteristics are divided into user interaction, charging status information displayed in the physical device, charging and construction data, communication protocols, incorporated smart features, and flexibility features.

Regarding user interaction, the majority of smart chargers are RFID (26/27 that means 26 out of 27) and mobile application (27/27) friendly, while a physical key (9/27) or pin code (5/27) is less spread. Similarly, LED lights that display the charging status are more often adopted (25/27) compared to physical displays (11/27). From this observation it seems that the future trend for user's interaction with smart chargers will be RFID and mobile applications, while for physical charging status, it will be LEDs. The latter one makes sense economically when comparing LEDs with physical displays.

Each single-phase charger has a 3-phase twin. Currently, the 22 kW charging power dominates over the 11 kW option (21 options for 22 kW towards 8 options for 11 kW). Although most of the chargers found are AC chargers (22/27), few DC chargers examples are also given (5/27).

Regarding the construction of physical chargers, charger manufactures are currently competing to make the chargers as light and as

Table 3
Advantages and drawbacks of EV chargers control approaches.

Control approach	Advantages	Drawbacks
Centralized	Vulnerable to cloud aggregator malfunction being spread on all chargers. System wide observation. Easier implementations of optimization algorithms.	Need of a backup server system. Heavy communication and computation when scaled-up. Subject to cyber-attacks and possible data privacy violation.
Decentralized	Diverts data privacy challenges. Low communications and computation capabilities when scaled-up. Low sensitivity to errors and cyber-attacks, thus high system robustness. High deployment scalability. Low communication delays.	Lack of grid observability. Immature control architecture. Risk of avalanche effects. Difficult to reach optimal solutions from optimization algorithms.
Distributed	High scalability and autonomy. System wide observation. Low sensitivity to errors, thus high system robustness. Diverts data privacy challenges. Possibility of plug and play protocols. Low communication delays.	Novel control architecture, thus not mature. Prone to cyber-attacks. High complexity on charger design.

small as possible. Although the lightest AC charger is 1 kg, the DC one is minimum 47 kg. For further details, refer to Table B.1. The minimum observed enclosure rating standard is IP54 and in six other charger alternatives, an improved standard followed (four options stick to IP55 and two options keep IP65). Further, 3 out of 27 chargers include cooling options, while all chargers embody DC current leakage protection and third category surge protection.

All the chargers presented in Table B.1 are controllable. According to the description of Open Charge Alliance, open charge point protocol (OCPP) is an open protocol that allows CPO to control the smart charger. Here, the smart chargers observed tend to converge to the OCPP 1.6 protocol that allows smart charging features [202]. Nevertheless, to be future-proof some manufactures have or are ready to implement OCPP 2.0, since the protocol was made available in April 2018. The OCPP 2.0 is designed to be flexibility friendly [203] and it offers improved functionalities such as device management, transaction handling, security, smart charging functionalities, ISO 15118 support, display and messaging support. Furthermore, five options are observed to be used to communicate and be integrated with external devices, namely 4G (24/27), WiFi (22/27), Ethernet (20/27), Bluetooth (11/27), and RS485 (10/27). The last two are range-limited alternatives. The typical example for such implementation is a local controller communication as displayed from Schneider EVlink smart charging controller [204].

Furthermore, the smart features section incorporated in Table B.2 attempts to distinguish the inputs each charger can receive and use in a decision-making process. First, the power set point (27/27) is a user or CPO reference input to follow. Second, the smart charger can receive consumption measurements from the energy meter (16/27), or otherwise, the charger has its own meter that closes the control loop. The home area network (HAN) protocol allows smart chargers to become part of a larger smart infrastructure. A majority (17/27) of chargers are HAN friendly meaning that they are able to communicate with other smart home devices. In addition, smart charging options can be provided, such as price-based charging (21/27) or power-sharing between devices or using local generation (14/27).

Lastly, flexibility features of the chargers are also provided, to recognize what flexibility capability each of the smart chargers offers. The scheduling feature is the minimum feature a charger needs to be called smart charger. In addition, 24 out of 27 chargers can modulate the charging current, while only three out of 27 can make the three to one phase charging switch.

6. Conclusions

By looking at the future of the power system, this study reviewed how smart chargers can be used to provide flexibility and what is the technology status at today. First, the ancillary services available in the power system are presented, by distinguishing between frequency and flexibility services. Then, these were discussed in terms of the type of action, namely frequency regulation, congestion management, voltage regulation, power quality, grid stability, and emission management. Five out of eight frequency services and 26 out of 32 flexibility services can be derived by EVs. However, only three out of eight frequency services the charging technology is on a commercial stage. Similarly for flexibility services, mainly congestion management services are being further developed for commercial applications. Furthermore, the study recommends that SOs should exhaust available non-market flexibility services before purchasing market-based flexibility.

In this sense, it is necessary to understand how EVs can provide these services. Thus, the supply chain of flexibility services from EVs is presented. Seven actors are identified: the end-user, the CSO, the CPO, the aggregator, the energy community, the DSO, and the TSO. The end-user is the main actor due to its large influence (charging behavior) on supply chain decisions. To link charging behavior and charging location clusters, 12 geo-electrical charging clusters (CSOs) are proposed. Additionally, the frequency and flexibility services are coupled with CSOs, and are matched with their grid location (low, medium, or high voltage).

To provide such services, CSOs can delegate their control to CPOs. CPOs can be further aggregated into energy communities or aggregators, and become a BRP to participate in electricity markets. However, to encourage the growth of the new technology/service provision, CPOs, charger manufacturers, and DSOs are forming alliances offering complete charging packages to the CSOs. Such packages include smart charging infrastructure and incentives to participate in ancillary services while bypassing current technological and market barriers.

Although, to perform ancillary services smart charger infrastructure is needed. Thus, this article provides an overview of current market available slow smart chargers with up to 50 kW. Three main flexibility features were observed to be commonly provided by the chargers: scheduling, modulation and switching from three-to-one phase during charging. All observed smart chargers can schedule, while 89% can also modulate. Only 10% can switch the charging from three-to-one phase.

Regarding future work, having a map of ancillary services coupled with EVs charging clusters opens up the door on one side for full exploitation of smart charging strategies and on the other side for different stakeholders to better understand their roles. Further, the available flexibility of each charging clusters needs to be quantified and proper smart charging strategies should be investigated to avoid avalanche or rebound effects. The Nordic case highlight the need for simple regulations to attract flexibility providers, looking primarily at congestion management actions. Novel approaches, such as flexibility alliances, bypass market barriers and bid size to help SOs gain confidence in flexibility service provisions. For example, Dansk Energi, an organization representing the Danish energy companies, is proposing a bid size of 10 kW, however, such approaches are still in the early stages. Lastly, smart charging infrastructure is developing rapidly. Most of the modern smart chargers are cloud-based and with a single outlet. To improve utilization factor and reduce the cost of smart chargers, double or quadruple outlets are being developed. In addition, new distributed controlled chargers are being investigated to tackle possible cyberattacks leading to a massive infrastructure being compromised.

CRediT authorship contribution statement

Kristian Sevdari: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. **Lisa Calearo:** Conceptualization, Methodology, Investigation, Writing – review & editing, Formal analysis. **Peter Bach Andersen:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. **Mattia Marinelli:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work in this article is supported by the research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092). We thank Alban Kuriqi and Mirko Ledro for providing valuable feedback and suggestions.

Appendix A. Examples of DSO flexibility services provision.

A.1. Congestion management

Fig. A.8(a) reflects the location and size domain, while Fig. A.8(b) reflects the time and size domain. The Frederiksberg distribution network comprises of three separate 10 kV networks supplied by a medium voltage transformer each [137]. The DSO congestion management can be first achieved from demand response programs, like ToU, or network reconfiguration on a wide area. For instance at Fig. A.8(a), ToU is activated but one of the three transformers, transformer X.5, is still overloaded, as shown in Fig. A.8(b). Thus on a second step,

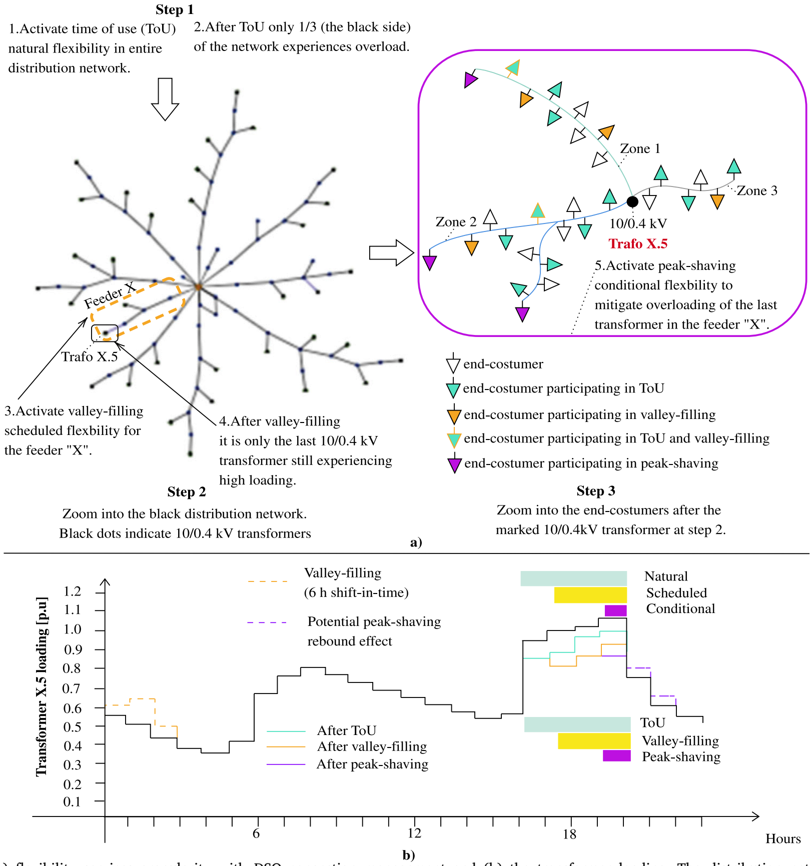


Fig. A.8. Illustration of (a) flexibility services granularity with DSO congestion management and (b) the transformer loading. The distribution network map is adapted with permission from [137].

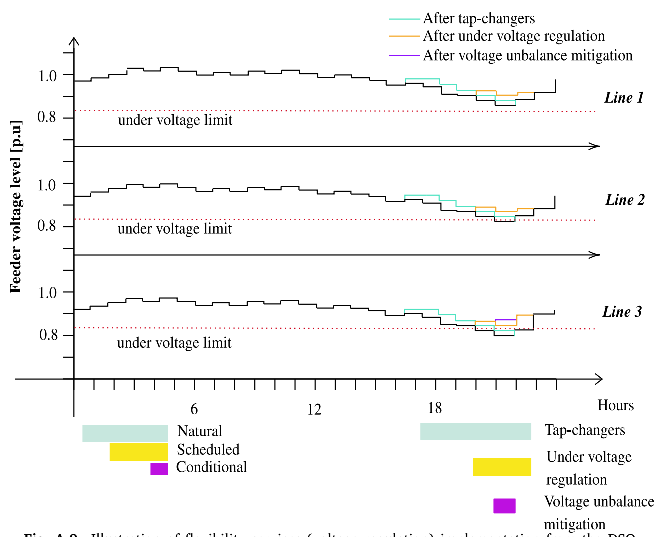


Fig. A.9. Illustration of flexibility services (voltage regulation) implementation from the DSO.

the DSO activates the procured services for feeder X, such as valley-filling. Transformer X.5 is still highly loaded, thus the activation of peak-shaving services closer to the location is required. Each flexibility service activation reflects a loading reduction. Nevertheless, the load reduction of each service is highly case dependent, so it is difficult to quantify before-hand. Further, the activation of the services could also cause rebound effects which should be carefully considered when designing these services [197].

A.2. Voltage regulation

Similarly, for an illustrative purpose in Fig. A.9, it is shown the voltage regulation activation. The DSO can activate voltage regulation in three steps. First, the DSO can remotely control the transformers' tap-changers. Second, the DSO can acquire market-based voltage regulation services like under-voltage regulation for the local area. Finally, if a more severe voltage unbalance is experienced the DSO can procure voltage unbalance mitigation services to recover the affected lines.

Appendix B. Overview of slow electric vehicles (EVs) smart chargers

See Tables B.1 and B.2.

References

[1] Lund H, Østergaard PA. Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation. Energy 2000;25(4):299–312.

[2] Lund H, Thellufsen JZ, Østergaard PA, Sorknæs P, Skov IR, Mathiesen BV. Energyplan–advanced analysis of smart energy systems. Smart Energy 2021;1:100007.

[3] Kondziella H, Bruckner T. Flexibility requirements of renewable energy based electricity systems - a review of research results and methodologies. Renew Sustain Energy Rev 2016;53:10–22. http://dx.doi.org/10.1016/j.rser.2015.07.199.

[4] Calearo L, Thingvad A, Suzuki K, Marinelli M. Grid loading due to EV charging profiles based on pseudo-real driving pattern and user behavior. IEEE Trans Transp Electrif 2019;5(3):683–94. http://dx.doi.org/10.1109/TTE.2019.2921854.

[5] Lopes JAP, Soares FJ, Almeida PMR. Integration of electric vehicles in the electric power system. Proc IEEE 2010;99(1):168–83.

[6] Hillberg E, Zegers A, Herndler B, Wong S, Pompee J, Bourmaud J-Y, Lehnhoff S, Migliavacca G, Uhlen K, Oleinikova I, et al. Flexibility needs in the future power system. ISGAN; 2019.

[7] Resch M, Buhler J, Schachler B, Sumper A. Techno-economic assessment of flexibility options versus grid expansion in distribution grids. IEEE Trans Power Syst 2021;36(5):3830–9. http://dx.doi.org/10.1109/TPWRS.2021.3055457.

[8] Mohandes B, Moursi MSE, Hatziargyriou N, Khatib SE. A review of power system flexibility with high penetration of renewables. IEEE Trans Power Syst 2019;34(4):3140–55. http://dx.doi.org/10.1109/TPWRS.2019.2897727.

Table B.1
Part 1 of the smart chargers technology overview. "Y" means yes, "N" means no and "NA" means the information is not available.

No	Type	Brand	Charger's name	User interaction				Status information			Power [kW]	Max current [A]	Phases	Voltage	Mode	Weight [kg]	Dimensions H × W × D [mm]	Enclosure rating
				RFID	App	Key	Pin code	LED	Display	AC(1) DC(0)								
1	V1G	ABB	Lunic	Y	Y	Y	N	Y	Y	1	4 to 22	16 and 32	1 and 3	240 and 400	3	NA	320 × 195 × 110	IP54
2	V1G	ABB	Terra AC wallbox	Y	Y	N	N	Y	N	1	7.4	32	1	240	3	2	320 × 195 × 110	IP54
3	V1G	ABB	Terra AC wallbox	Y	Y	N	N	Y	N	1	22	32	3	400	3	3.5	320 × 195 × 110	IP54
4	V1G	ABB	Terra DC wallbox	Y	Y	Y	Y	Y	Y	0	24	40	1	240	4	60	770 × 584 × 294	IP54
5	V1G	ABB	Terra DC wallbox	Y	Y	Y	Y	Y	Y	0	24	40	3	400	4	60	770 × 584 × 294	IP54
6	V1G	CHP	CP4100	Y	Y	Y	N	Y	Y	1	3.7 to 22.17	16 and 32	1 and 3	240 and 400	3	NA	491 × 189 × 189	IP54
7	V1G	Delta	Mini AC	Y	Y	N	N	Y	N	1	7.4	32	1	240	3	2	260 × 320 × 115	IP54
8	V1G	Delta	Wallbox	Y	Y	Y	N	Y	Y	0	7.4 and 22.17	32	1 and 3	240 and 400	4	47	680 × 430 × 230	IP54
9	V1G	EVBox	Elvi	Y	Y	Y	N	Y	N	1	3.7 and 7.4	16 and 32	1	230	3	3	186 × 328 × 161	IP55
10	V1G	EVBox	Elvi	Y	Y	Y	N	Y	N	1	11 and 22	16 and 32	3	400	3	6	186 × 328 × 161	IP55
11	V1G	EVBox	Business	Y	Y	N	N	Y	N	1	7.4	32	1	230	3	10	600 × 255 × 410	IP55
12	V1G	EVBox	Business	Y	Y	N	N	Y	N	1	11 and 22	16 and 32	3	400	3	12	600 × 255 × 410	IP55
13	V1G	Kempower	T500-DC	Y	Y	N	N	Y	Y	0	40	63	3	400	4	120	670 × 640 × 1220	IP54
14	V1G	Kempower	T800-DC	Y	Y	N	N	Y	Y	0	40	63	3	400	4	120	670 × 640 × 1220	IP54
15	V1G	Myenergi	Zappi	Y	Y	N	Y	Y	Y	1	7.4	32	1	230	3	NA	439 × 282 × 122	IP65
16	V1G	Myenergi	Zappi	Y	Y	N	Y	Y	Y	1	22	32	3	400	3	NA	439 × 282 × 122	IP65
17	V1G	Schneider	EVlink	Y	Y	Y	N	N	N	1	7.4	32	1	230	3	NA	157 × 150 × 46	IP54
18	V1G	Schneider	EVlink	Y	Y	Y	N	N	N	1	22	32	3	400	3	NA	157 × 150 × 46	IP54
19	V1G	Siemens	VersiCharge	Y	Y	N	N	Y	N	1	7.4	16	1	230	2	7.7	410 × 180 × 100	IP54
20	V1G	Siemens	VersiCharge	Y	Y	N	N	Y	N	1	11 and 22	16 and 32	3	400	2	7.7	410 × 180 × 100	IP54
21	V1G	Zaptec	Pro	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	5	392 × 258 × 112	IP54
22	V1G	Zaptec	Go	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	1.3	242 × 180 × 75	IP54
23	V1G	Virta	Single	Y	Y	N	N	Y	Y	1	7.4 and 22	32	1 and 3	230 and 400	3	NA	370 × 240 × 130	IP54
24	V1G	Wallbox	Pulsar plus	N	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	1	166 × 163 × 88	IP54
25	V1G	Wallbox	Copper SB	Y	Y	N	N	Y	N	1	7.4 and 22	32	1 and 3	230 and 400	3	2	260 × 192 × 113	IP54
26	V1G	Wallbox	Commander 2	Y	Y	N	Y	Y	Y	1	7.4 and 22	32	1 and 3	230 and 400	3	24	221 × 152 × 115	IP54
27	V1G	Fronius	Wattpilot	Y	Y	N	N	Y	N	1	3.7 and 11	16	1 and 3	230 and 400	3	1.9	251 × 146 × 96	IP54

Table B.2
Part 2 of the smart chargers technology overview. "Y" means yes, "N" means no and "NA" means the information is not available. To the reader please keep track with Table 3 via the corresponding charger number.

No	Controllable Yes/No	OCPP	Communication						Surge category	Leakage protection	Incorporated smart features					Flexibility feature		
			4G	Wifi	Ethernet (RJ45)	Bluetooth	RS485	Cooling Yes/No			Power setpoint	Data from energy-meter	HAN friendly	Price based	Power share	Scheduling	Modulation	3 to 1 phase switch
1	Y	1.6	Y	N	Y	N	N	N	3	Y	Y	N	N	N	N	Y	Y	N
2	Y	1.6	Y	Y	Y	Y	Y	N	3	Y	Y	N	N	N	N	Y	Y	N
3	Y	1.6	Y	Y	Y	Y	Y	N	3	Y	Y	N	N	N	N	Y	Y	N
4	Y	1.5/1.6/2.0	Y	N	Y	N	N	N	3	Y	Y	Y	Y	Y	N	Y	Y	N
5	Y	1.5/1.6/2.0	Y	N	Y	N	N	N	3	Y	Y	Y	Y	Y	N	Y	Y	N
6	Y	1.6	Y	N	N	N	N	N	3	Y	Y	N	N	Y	Y	Y	Y	N
7	Y	1.5	Y	N	Y	N	N	N	3	Y	Y	N	N	N	N	Y	Y	N
8	Y	1.5	Y	Y	Y	N	N	Y	3	Y	Y	N	N	N	N	Y	N	N
9	Y	1.5 S/1.6 J	N	Y	N	Y	Y	N	3	Y	Y	Y	Y	Y	N	Y	Y	N
10	Y	1.5 S/1.6 J	N	Y	N	Y	Y	N	3	Y	Y	Y	Y	Y	N	Y	Y	N
11	Y	1.5S/ 1.6S/1.6J	Y	Y	N	Y	N	N	3	Y	Y	N	N	Y	N	Y	Y	N
12	Y	1.6	Y	Y	N	Y	N	N	3	Y	Y	N	N	Y	N	Y	Y	N
13	Y	1.6	Y	Y	Y	N	N	Y	3	Y	Y	Y	Y	Y	N	Y	N	N
14	Y	1.6	Y	Y	Y	N	N	Y	3	Y	Y	Y	Y	Y	N	Y	N	N
15	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
16	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
17	Y	1.5/1.6 J	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
18	Y	1.5/1.6 J	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
19	Y	1.6	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
20	Y	1.6	Y	Y	Y	N	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
21	Y	1.6 J	Y	Y	Y	Y	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y
22	Y	1.6 J	Y	Y	Y	Y	Y	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y
23	Y	1.6	Y	Y	N	N	N	N	3	Y	Y	N	N	Y	Y	Y	Y	N
24	Y	1.6	N	Y	N	Y	N	N	3	Y	Y	N	N	N	Y	Y	Y	N
25	Y	1.6	Y	Y	Y	Y	N	N	3	Y	Y	N	Y	Y	Y	Y	Y	N
26	Y	1.6	Y	Y	Y	Y	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	N
27	Y	1.6	Y	Y	Y	N	N	N	3	Y	Y	Y	Y	Y	Y	Y	Y	Y

[9] Degefa MZ, Sperstad IB, Sæle H. Comprehensive classifications and characterizations of power system flexibility resources. Electr Power Syst Res 2021;194(January):107022. http://dx.doi.org/10.1016/j.epsr.2021.107022.
[10] Lannoye E, Flynn D, O'Malley M. Evaluation of power system flexibility. IEEE Trans Power Syst 2012;27(2):922–31.
[11] Jin X, Wu Q, Jia H. Local flexibility markets: Literature review on concepts, models and clearing methods. Appl Energy 2020;261(August 2019):114387. http://dx.doi.org/10.1016/j.apenergy.2019.114387.
[12] Villar J, Bessa R, Matos M. Flexibility products and markets: Literature review. Electr Power Syst Res 2018;154:329–40. http://dx.doi.org/10.1016/j.epsr.2017.09.005.
[13] Papaefthymiou G, Haesen E, Sach T. Power system flexibility tracker: Indicators to track flexibility progress towards high-RES systems. Renew Energy 2018;127:1026–35. http://dx.doi.org/10.1016/j.renene.2018.04.094.
[14] Ela E, Milligan M, Bloom A, Botterud A, Townsend A, Levin T. Evolution of wholesale electricity market design with increasing levels of renewable generation. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2014.
[15] Østergaard J, Ziras C, W.Bindner H, Kazempour J, Marinelli M, Markussen P, Horn Rosted S, S. Christensen J. Energy security through demand-side flexibility: The case of Denmark. IEEE Power Energy Mag 2021;19(april):46–55.
[16] Cruz MR, Fitiwi DZ, Santos SF, Catalão JP. A comprehensive survey of flexibility options for supporting the low-carbon energy future. Renew Sustain Energy Rev 2018;97(August):338–53. http://dx.doi.org/10.1016/j.rser.2018.08.028.
[17] Hamwi M, Lizarralde I, Legardeur J. Demand response business model canvas: A tool for flexibility creation in the electricity markets. J Cleaner Prod 2021;282. http://dx.doi.org/10.1016/j.jclepro.2020.124539.
[18] Klyapovskiy S, You S, Michiorri A, Kariniotakis G, Bindner HW. Incorporating flexibility options into distribution grid reinforcement planning: A techno-economic framework approach. Appl Energy 2019;254(August):113662. http://dx.doi.org/10.1016/j.apenergy.2019.113662.
[19] Lannoye E, Daly P, Tuohy A, Flynn D, O'Malley M. Assessing power system flexibility for variable renewable integration: A flexibility metric for long-term system planning. CIGRE Sci Eng J 2015;3:26–39.
[20] British Standard Institution. PAS 1879:2021, Energy smart appliances – demand side response operation – code of practice. In: tech. rep.. 2021.
[21] Dansk Energi. Industry guidance for network companies on procurement of flexibility services - first draft. (June). 2021.
[22] Heinrich C, Ziras C, Syrri AL, Bindner HW. EcoGrid 2.0: A Large-scale field trial of a local flexibility market. Appl Energy 2020;261(December 2019):114399. http://dx.doi.org/10.1016/j.apenergy.2019.114399.
[23] Tan KM, Ramachandaramurthy VK, Yong JY. Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. Renew Sustain Energy Rev 2016;53:720–32.
[24] Gonzalez Venegas F, Petit M, Perez Y. Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services. Renew Sustain Energy Rev 2021;145(March):111060. http://dx.doi.org/10.1016/j.rser.2021.111060.
[25] Neaimeh M, Andersen PB. Mind the gap- open communication protocols for vehicle grid integration. Energy Informatics 2020;3(1):1–17. http://dx.doi.org/10.1186/s42162-020-0103-1.
[26] Metere R, Neaimeh M, Morisset C, Maple C, Bellekens X, Czekster RM. Securing the electric vehicle charging infrastructure. 2021, arXiv preprint arXiv:2105.02905.
[27] Deason W. Comparison of 100% renewable energy system scenarios with a focus on flexibility and cost. Renew Sustain Energy Rev 2018;82:3168–78.
[28] Anwar MB, Muratori M, Jadun P, Hale E, Bush B, Denholm P, Ma O, Podkaminer K. Assessing the value of electric vehicle managed charging: a review of methodologies and results. Energy Environ Sci 2022;15(2):466–98. http://dx.doi.org/10.1039/d1ee02206g.
[29] Parliament E. Directive 2019/944 on common rules for the internal market for electricity. Official J European Union 2019;(L 158/125):18.
[30] Stian H, Heidi A, Hanne G, Espen D. Market based flexibility procurement for Nordic DSOs. tech. rep., 2021.
[31] Misconel S, Zöphel C, Möst D. Assessing the value of demand response in a decarbonized energy system–a large-scale model application. Appl Energy 2021;299:117326.
[32] Gunkel PA, Bergaentzlé C, Græsted Jensen I, Scheller F. From passive to active: Flexibility from electric vehicles in the context of transmission system development. Appl Energy 2020;277(June):115526. http://dx.doi.org/10.1016/j.apenergy.2020.115526.
[33] Jakobsen S, Flader L, Andersen P, Thingvad A, Bollerslev J. Sådan skaber danmark grøn infrastruktur til én million elbiler: Analyse og anbefalinger fra DEA og DTU, november 2019. Technical University of Denmark; 2020.
[34] Neaimeh M, Wardle R, Jenkins AM, Yi J, Hill G, Lyons PF, Hübner Y, Blythe PT, Taylor PC. A probabilistic approach to combining smart meter and electric vehicle charging data to investigate distribution network impacts. Appl Energy 2015;157:688–98. http://dx.doi.org/10.1016/j.apenergy.2015.01.144.
[35] Landi M, InnovateUK. V2G benefits and learnings. In: Tec. rep.. Innovate UK: Innovate UK; 2020.
[36] Habib S, Khan MM, Abbas F, Sang L, Shahid MU, Tang H. A comprehensive study of implemented international standards, technical challenges, impacts and prospects for electric vehicles. IEEE Access 2018;6:13866–90. http://dx.doi.org/10.1109/ACCESS.2018.2812303.
[37] Calearo L, Ziras C, Sevdari K, Marinelli M. Comparison of smart charging and battery energy storage system for a pv prosumer with an EV. In: 2021 IEEE PES Innovative Smart Grid Technologies Conference Europe. IEEE; 2021.
[38] Energinet. Technical regulation 3-3-1 for electrical energy storage facilities. 2019;May:19. http://dx.doi.org/10.16141/j.cnki.1671-8089.2019.07.030.
[39] Sencar M, Pozeb V, Krope T. Development of EU (European union) energy market agenda and security of supply. Energy 2014;77:117–24. http://dx.doi.org/10.1016/j.energy.2014.05.031.
[40] Kundur P, Paserba J, Ajjarapu V, Andersson G, Bose A, Canizares C, Hatziargyriou N, Hill D, Stankovic A, Taylor C, et al. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. IEEE Trans Power Syst 2004;19(3):1387–401.
[41] Hatziargyriou N, Milanovic J, Rahmann C, Ajjarapu V, Canizares C, Erlich I, Hill D, Hiskens I, Kamwa I, Pal B, et al. Definition and classification of power system stability revisited & extended. IEEE Trans Power Syst 2020.
[42] Panteli M, Mancarella P, Trakas DN, Kyriakides E, Hatziargyriou ND. Metrics and quantification of operational and infrastructure resilience in power systems. IEEE Trans Power Syst 2017;32(6):4732–42. http://dx.doi.org/10.1109/TPWRS.2017.2664141.
[43] Oureilidis K, Malamaki KN, Gallos K, Tsitsimelis A, Dikaiakos C, Gkavanoudis S, Cvetkovic M, Mauricio JM, Ortega JMM, Ramos JLM, Papaioannou G, Demoulias C. Ancillary services market design in distribution networks: Review and identification of barriers. Energies 2020;13(4). http://dx.doi.org/10.3390/en13040917.
[44] Rebours YG, Kirschen DS, Trotignon M, Rossignol S. A survey of frequency and voltage control ancillary services - Part I: Technical features. IEEE Trans Power Syst 2007;22(1):350–7. http://dx.doi.org/10.1109/TPWRS.2006.888963.
[45] Rebours YG, Kirschen DS, Trotignon M, Rossignol S. A survey of frequency and voltage control ancillary services - Part II: Economic features. IEEE Trans Power Syst 2007;22(1):358–66. http://dx.doi.org/10.1109/TPWRS.2006.888965.
[46] Kotsampopoulos P, Hatziargyriou N, Bletterie B, Lauss G. Review, analysis and recommendations on recent guidelines for the provision of ancillary services by distributed generation. In: Proceedings - 2013 IEEE International Workshop on Intelligent Energy Systems, IWIES 2013. IEEE; 2013, p. 185–90. http://dx.doi.org/10.1109/IWIES.2013.6698583.
[47] Kryonidis GC, Kontis EO, Papadopoulos TA, Pippi KD, Nousdilis AI, Barzegkar-Ntovom GA, Boubaris AD, Papanikolaou NP. Ancillary services in active distribution networks: A review of technological trends from operational and online analysis perspective. Renew Sustain Energy Rev 2021;147(May):111198. http://dx.doi.org/10.1016/j.rser.2021.111198.
[48] Mai T, Hand MM, Baldwin SF, Wiser RH, Brinkman GL, Denholm P, Arent DJ, Porro G, Sandor D, Hostick DJ, et al. Renewable electricity futures for the United States. IEEE Trans Sustain Energy 2013;5(2):372–8.
[49] Fernández-Guillamón A, Gómez-Lázaro E, Muljadi E, Molina-García A. Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. Renew Sustain Energy Rev 2019;115(August):109369. http://dx.doi.org/10.1016/j.rser.2019.109369.
[50] Hirth L, Ziegenhagen I. Balancing power and variable renewables: Three links. Renew Sustain Energy Rev 2015;50:1035–51. http://dx.doi.org/10.1016/j.rser.2015.04.180.
[51] Adrees A, Papadopoulos PN, Milanovic JV. A framework to assess the effect of reduction in inertia on system frequency response. In: 2016 IEEE Power and Energy Society General Meeting (PESGM). IEEE; 2016, p. 1–5.
[52] Huang H, Li F. Sensitivity analysis of load-damping characteristic in power system frequency regulation. IEEE Trans Power Syst 2012;28(2):1324–35.
[53] Milano F, Dörfler F, Hug G, Hill DJ, Verbič G. Foundations and challenges of low-inertia systems. In: 2018 Power systems computation conference (PSCC). IEEE; 2018, p. 1–25.
[54] Ulbig A, Borsche TS, Andersson G. Impact of low rotational inertia on power system stability and operation. IFAC Proc Vol 2014;47(3):7290–7.
[55] De Boeck S, Das K, Trovato V, Turunen J, Halat M, Sorensen P, Van Hertem D. Review of defence plans in europe: Current status, strenghts and opportunities. CIGRE Sci Eng 2016;5:6–16.
[56] Mancarella P, Puschel S, Zhang L, Wang H, Brear M, Jones T, Jeppesen M, Batterham R, Evans R, Mareels I. Power system security assessment of the future national electricity market. University of Melbourne 2017.
[57] Modig N, Eriksson R, Haarla L, Ruokolainen P, Kuivaniemi M, Hornnes K, Vada P, Meybodi S, Karlsson D. Technical requirements for fast frequency reserve provision in the Nordic synchronous area. Techical Report for Fingrid 2019.
[58] Statnett. Fast frequency reserves 2018 - pilot for raske frekvensreserver. In: tech. rep.. 2018, p. 1–36.
[59] Rezkalla M, Pertl M, Marinelli M. Electric power system inertia: requirements, challenges and solutions. Electr Eng 2018;100(4):2677–93. http://dx.doi.org/10.1007/s00202-018-0739-z.

[60] Tamrakar U, Shrestha D, Maharjan M, Bhattarai BP. Virtual inertia : Current trends and future directions. Appl Sci 2017;1–29. http://dx.doi.org/10.3390/app7070654.
[61] Gonzalez-Longatt F. Frequency control and inertial response schemes for the future power networks. In: Large Scale Renewable Power Generation. Springer; 2014, p. 193–231.
[62] NERC. Fast frequency response concepts and bulk power system reliability needs. NERC Inverter-Based Resource Performance Task Force (IRPTF) 2020;(March):1–23.
[63] Du P, Mago NV, Li W, Sharma S, Hu Q, Ding T. New ancillary service market for ERCOT. IEEE Access 2020;8:178391–401.
[64] Everoze. Batteries: Beyond the spin - the dawning era of digital inertia on the island of Ireland. (October). 2017.
[65] Fernández-Muñoz D, Pérez-Díaz JI, Guisández I, Chazarra M, Fernández-Espina A. Fast frequency control ancillary services: An international review. Renew Sustain Energy Rev 2020;120(December 2019). http://dx.doi.org/10.1016/j.rser.2019.109662.
[66] Eto JH, Undrill J, Roberts C, Mackin P, Ellis J. Frequency control requirements for reliable interconnection frequency response. 2018.
[67] Díaz-González F, Hau M, Sumper A, Gomis-Bellmunt O. Participation of wind power plants in system frequency control: Review of grid code requirements and control methods. Renew Sustain Energy Rev 2014;34:551–64.
[68] ENTSO-E. Operational reserve ad hoc team report. 2012, p. 1–58.
[69] ENTSO-E. Fast frequency reserve – solution to the nordic inertia challenge. In: Tech. Rep.. (December):2019, p. 1–22.
[70] National Grid ESO. Dynamic containment - overview. In: Tech. Rep.. (January). 2021.
[71] Tielens P, Van Hertem D. The relevance of inertia in power systems. Renew Sustain Energy Rev 2016;55(2016):999–1009. http://dx.doi.org/10.1016/j.rser.2015.11.016.
[72] Nguyen HT, Chleirigh MN, Yang G. A technical economic evaluation of inertial response from wind generators and synchronous condensers. IEEE Access 2021;9:7183–92. http://dx.doi.org/10.1109/ACCESS.2021.3049197.
[73] Eriksson R, Modig N, Elkington K. Synthetic inertia versus fast frequency response: a definition. IET Renew Power Gener 2018;12(5):507–14.
[74] Rezkalla M, Zecchino A, Martinenas S, Prostejovsky AM, Marinelli M. Comparison between synthetic inertia and fast frequency containment control based on single phase EVs in a microgrid. Appl Energy 2018;210:764–75.
[75] Zuo Y, Yuan Z, Sossan F, Zecchino A, Cherkaoui R, Paolone M. Performance assessment of grid-forming and grid-following converter-interfaced battery energy storage systems on frequency regulation in low-inertia power grids. Sustain Energy, Grids and Networks 2021;27:100496. http://dx.doi.org/10.1016/j.segan.2021.100496.
[76] Tamrakar U, Shrestha D, Maharjan M, Bhattarai BP, Hansen TM, Tonkoski R. Virtual inertia: Current trends and future directions. Appl Sci 2017;7(7):654.
[77] Nguyen HT, Yang G, Nielsen AH, Jensen PH, Pal B. Applying synchronous condenser for damping provision in converter-dominated power system. J Mod Power Syst Clean Energy 2021;9(3):639–47. http://dx.doi.org/10.35833/MPCE.2020.000207.
[78] Marinelli M, Sevdari K, Calearo L, Thingvad A, Ziras C. Frequency stability with converter-connected resources delivering fast frequency control. Electr Power Syst Res 2021;200(July):107473. http://dx.doi.org/10.1016/j.epsr.2021.107473.
[79] Thingvad A, Ziras C, Marinelli M. Economic value of electric vehicle reserve provision in the nordic countries under driving requirements and charger losses. J Energy Storage 2019;21(December 2018):826–34. http://dx.doi.org/10.1016/j.est.2018.12.018.
[80] Marinelli M, Martinenas S, Knezović K, Andersen PB. Validating a centralized approach to primary frequency control with series-produced electric vehicles. J Energy Storage 2016;7:63–73.
[81] TenneT TSO BV. aFRR pilot end report. 2021, p. 1–37.
[82] Fan H, Jiang L, Zhang CK, Mao C. Frequency regulation of multi-area power systems with plug-in electric vehicles considering communication delays. IET Gener, Trans Distrib 2016;10(14):3481–91. http://dx.doi.org/10.1049/iet-gtd.2016.0108.
[83] Statnett SF. Distributed balancing of the power grid. (February):2021, p. 1–48.
[84] Aigner T, Jaehnert S, Doorman GL, Gjengedal T. The effect of large-scale wind power on system balancing in Northern Europe. IEEE Trans Sustain Energy 2012;3(4):751–9.
[85] Rajan R, Fernandez FM, Yang Y. Primary frequency control techniques for large-scale PV-integrated power systems: A review. Renew Sustain Energy Rev 2021;144:110998.
[86] Dreidy M, Mokhlis H, Mekhilef S. Inertia response and frequency control techniques for renewable energy sources: A review. Renew Sustain Energy Rev 2017;69(July 2016):144–55. http://dx.doi.org/10.1016/j.rser.2016.11.170.
[87] Shi Q, Li F, Hu Q, Wang Z. Dynamic demand control for system frequency regulation: Concept review, algorithm comparison, and future vision. Electr Power Syst Res 2018;154:75–87. http://dx.doi.org/10.1016/j.epsr.2017.07.021.
[88] ENTSO-E. Supporting document for the network code on load-frequency control and reserves (NC LFCR). 2013, p. 156.
[89] Duckwitz D, Fischer B. Modeling and design of df/dt-based inertia control for power converters. IEEE J. Emerg Select Top Power Electr 2017;5(4):1553–64.
[90] Liu J, Miura Y, Bevrani H, Ise T. Enhanced virtual synchronous generator control for parallel inverters in microgrids. IEEE Trans Smart Grid 2016;8(5):2268–77.
[91] Seo G-S, Colombino M, Subotic I, Johnson B, Groß D, Dörfler F. Dispatchable virtual oscillator control for decentralized inverter-dominated power systems: Analysis and experiments. In: 2019 IEEE applied power electronics conference and exposition (APEC). IEEE; 2019, p. 561–6.
[92] Matevosyan J, MacDowell J, Miller N, Badrzadeh B, Ramasubramanian D, Isaacs A, Quint R, Quitmann E, Pfeiffer R, Urdal H, et al. A future with inverter-based resources: Finding strength from traditional weakness. IEEE Power Energy Mag 2021;19(6):18–28.
[93] Institute of Electrical and Electronics Engineers. Ieee std 1159 - ieee recommended practice for monitoring electric power quality. In: IEEE Std 1159-2019 (Revision of IEEE Std 1159-2009). vol. 2019, (June):2019, p. 1–98. http://dx.doi.org/10.1109/IEEESTD.2009.5154067.
[94] Borne O, Korte K, Perez Y, Petit M, Purkus A. Barriers to entry in frequency-regulation services markets: Review of the status quo and options for improvements. Renew Sustain Energy Rev 2018;81(July 2016):605–14. http://dx.doi.org/10.1016/j.rser.2017.08.052.
[95] Rancilio G, Rossi A, Falabretti D, Galliani A, Merlo M. Ancillary services markets in europe: Evolution and regulatory trade-offs. Renew Sustain Energy Rev 2022;154(September 2021):111850. http://dx.doi.org/10.1016/j.rser.2021.111850.
[96] Honarmand ME, Hosseinnezhad V, Hayes B, Shafie-Khah M, Siano P. An overview of demand response: From its origins to the smart energy community. IEEE Access 2021;9:96851–76. http://dx.doi.org/10.1109/ACCESS.2021.3094090.
[97] Albadi MH, El-Saadany EF. A summary of demand response in electricity markets. Electr Power Syst Res 2008;78(11):1989–96. http://dx.doi.org/10.1016/j.epsr.2008.04.002.
[98] Huang S, Wu Q, Shahidehpour M, et al. Dynamic power tariff for congestion management in distribution networks. IEEE Trans Smart Grid 2018;10(2):2148–57.
[99] Shariatzadeh F, Mandal P, Srivastava AK. Demand response for sustainable energy systems: A review, application and implementation strategy. Renew Sustain Energy Rev 2015;45:343–50. http://dx.doi.org/10.1016/j.rser.2015.01.062.
[100] Ghazvini MAF, Lipari G, Pau M, Ponci F, Monti A, Soares Ja, Castro R, Vale Z. Congestion management in active distribution networks through demand response implementation. Sustain Energy, Grids and Networks 2019;17:100185.
[101] Dixon J, Bukhsh W, Edmunds C, Bell K. Scheduling electric vehicle charging to minimise carbon emissions and wind curtailment. Renew Energy 2020;161:1072–91. http://dx.doi.org/10.1016/j.renene.2020.07.017.
[102] Huang S, Wu Q, Liu Z, Nielsen AH. Review of congestion management methods for distribution networks with high penetration of distributed energy resources. In: IEEE PES innovative smart grid technologies, Europe. IEEE; 2014, p. 1–6.
[103] De Carne G, Liserre M, Christakou K, Paolone M. Integrated voltage control and line congestion management in active distribution networks by means of smart transformers. In: 2014 IEEE 23rd international symposium on industrial electronics (ISIE). IEEE; 2014, p. 2613–9.
[104] Lee C-T, Hsu C-W, Cheng P-T. A low-voltage ride-through technique for grid-connected converters of distributed energy resources. IEEE Trans Ind Appl 2011;47(4):1821–32.
[105] Uthra R, Suchitra D, et al. Fault ride through in grid integrated hybrid system using FACTS device and electric vehicle charging station. Energies 2021;14(13):3828.
[106] Velasco D, Trujillo C, Garcerá G, Figueres E. Review of anti-islanding techniques in distributed generators. Renew Sustain Energy Rev 2010;14(6):1608–14.
[107] Li K, Liu J, Wang Z, Wei B. Strategies and operating point optimization of STATCOM control for voltage unbalance mitigation in three-phase three-wire systems. IEEE Trans Power Deliv 2006;22(1):413–22.
[108] Li J, Liu F, Li Z, Shao C, Liu X. Grid-side flexibility of power systems in integrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches. Renew Sustain Energy Rev 2018;93(April):272–84. http://dx.doi.org/10.1016/j.rser.2018.04.109.
[109] Tan KM, Padmanaban S, Yong JY, Ramachandaramurthy VK. A multi-control vehicle-to-grid charger with bi-directional active and reactive power capabilities for power grid support. Energy 2019;171:1150–63.
[110] Kesler M, Kisacikoglu MC, Tolbert LM. Vehicle-to-grid reactive power operation using plug-in electric vehicle bidirectional offboard charger. IEEE Trans Ind Electron 2014;61(12):6778–84.
[111] Johal R, Ravi, Jain DK. Demand response as a load shaping tool integrating electric vehicles. In: 2016 IEEE 6th International Conference on Power Systems, ICPS 2016. 2, (4):IEEE; 2016, p. 624–31. http://dx.doi.org/10.1109/ICPES.2016.7584024.
[112] Ioakimidis CS, Thomas D, Rycerski P, Genikomsakis KN. Peak shaving and valley filling of power consumption profile in non-residential buildings using an electric vehicle parking lot. Energy 2018;148:148–58. http://dx.doi.org/10.1016/j.energy.2018.01.128.

[113] Zhang K, Xu L, Ouyang M, Wang H, Lu L, Li J, Li Z. Optimal decentralized valley-filling charging strategy for electric vehicles. Energy Convers Manage 2014;78:537–50. http://dx.doi.org/10.1016/j.enconman.2013.11.011.
[114] Knezović K, Marinelli M. Phase-wise enhanced voltage support from electric vehicles in a danish low-voltage distribution grid. Electr Power Syst Res 2016;140:274–83. http://dx.doi.org/10.1016/j.epsr.2016.06.015.
[115] Zecchino A, Marinelli M. Analytical assessment of voltage support via reactive power from new electric vehicles supply equipment in radial distribution grids with voltage-dependent loads. Int J Electr Power Energy Syst 2018;97(September 2017):17–27. http://dx.doi.org/10.1016/j.ijepes.2017.10.034.
[116] Reihani E, Motalleb M, Ghorbani R, Saoud LS. Load peak shaving and power smoothing of a distribution grid with high renewable energy penetration. Renew Energy 2016;86:1372–9.
[117] Deilami S, Masoum AS, Moses PS, Masoum MA. Voltage profile and THD distortion of residential network with high penetration of plug-in electrical vehicles. In: 2010 IEEE pes innovative smart grid technologies conference Europe (ISGT Europe). IEEE; 2010, p. 1–6.
[118] Crozier C, Deakin M, Morstyn T, McCulloch M. Coordinated electric vehicle charging to reduce losses without network impedances. IET Smart Grid 2020;3(5):677–85. http://dx.doi.org/10.1049/iet-stg.2019.0216.
[119] Sortomme E, Hindi MM, MacPherson SD, Venkata SS. Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses. IEEE Trans Smart Grid 2011;2(1):198–205. http://dx.doi.org/10.1109/TSG.2010.2090913.
[120] Ghofrani M, Arabali A, Etezadi-Amoli M, Fadali MS. Smart scheduling and cost-benefit analysis of grid-enabled electric vehicles for wind power integration. IEEE Trans Smart Grid 2014;5(5):2306–13.
[121] Howlader AM, Urasaki N, Yona A, Senjyu T, Saber AY. A review of output power smoothing methods for wind energy conversion systems. Renew Sustain Energy Rev 2013;26:135–46.
[122] Fazelpour F, Vafaeipour M, Rahbari O, Rosen MA. Intelligent optimization to integrate a plug-in hybrid electric vehicle smart parking lot with renewable energy resources and enhance grid characteristics. Energy Convers Manage 2014;77:250–61.
[123] Bai H, Taylor A, Guo W, Szatmari-Voicu G, Wang N, Patterson J, Kane J. Design of an 11 kw power factor correction and 10 kW ZVS DC/DC converter for a high-efficiency battery charger in electric vehicles. IET Power Electronics 2012;5(9):1714–22.
[124] Sarker MR, Olsen DJ, Ortega-Vazquez MA. Co-optimization of distribution transformer aging and energy arbitrage using electric vehicles. IEEE Trans Smart Grid 2016;8(6):2712–22.
[125] Palizban O, Kauhaniemi K. Energy storage systems in modern grids—Matrix of technologies and applications. J Energy Storage 2016;6:248–59.
[126] Bozalakov D, Laveyne J, Desmet J, Vandevelde L. Overvoltage and voltage unbalance mitigation in areas with high penetration of renewable energy resources by using the modified three-phase damping control strategy. Electr Power Syst Res 2019;168:283–94.
[127] Knezović K, Martinenas S, Andersen PB, Zecchino A, Marinelli M. Enhancing the role of electric vehicles in the power grid: field validation of multiple ancillary services. IEEE Trans Transp Electrif 2016;3(1):201–9.
[128] Martinenas S, Knezović K, Marinelli M. Management of power quality issues in low voltage networks using electric vehicles: Experimental validation. IEEE Trans Power Deliv 2016;32(2):971–9.
[129] Grau I, Skarvelis-Kazakos S, Papadopoulos P, Cipcigan L, Jenkins N. Electric vehicles support for intentional islanding: A prediction for 2030. In: 41st North American power symposium. IEEE; 2009, p. 1–5.
[130] Hussain SM, Aftab MA, Ali I, Ustun TS. IEC 61850 Based energy management system using plug-in electric vehicles and distributed generators during emergencies. Int J Electr Power Energy Syst 2020;119(January):105873. http://dx.doi.org/10.1016/j.ijepes.2020.105873.
[131] Richardson DB. Electric vehicles and the electric grid: A review of modeling approaches, impacts, and renewable energy integration. Renew Sustain Energy Rev 2013;19:247–54. http://dx.doi.org/10.1016/j.rser.2012.11.042.
[132] Lico P, Marinelli M, Knezović K, Grillo S. Phase balancing by means of electric vehicles single-phase connection shifting in a low voltage danish grid. In: 2015 50th international universities power engineering conference (UPEC). IEEE; 2015, p. 1–5.
[133] Crozier C, Morstyn T, McCulloch M. The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems. Appl Energy 2020;268(March):114973. http://dx.doi.org/10.1016/j.apenergy.2020.114973.
[134] Lopes JP, Almeida PMR, Silva AM, Soares FJ. Smart charging strategies for electric vehicles: Enhancing grid performance and maximizing the use of variable renewable energy resources. 2009.
[135] Akhavan-Rezai E, Shaaban M, El-Saadany E, Zidan A. Uncoordinated charging impacts of electric vehicles on electric distribution grids: Normal and fast charging comparison. In: 2012 IEEE power and energy society general meeting. IEEE; 2012, p. 1–7.
[136] Hilshey AD, Rezaei P, Hines PD, Frolik J. Electric vehicle charging: Transformer impacts and smart, decentralized solutions. In: 2012 IEEE power and energy society general meeting. IEEE; 2012, p. 1–8.
[137] Unterluggauer T, Klyapovskiy S, Hipolito F, Andersen PB. Impact of electric vehicle charging coordination on the power distribution network of frederiksberg. In: EVS35 international battery, hybrid and fuel cell electric vehicle symposium. 2022, under-review.
[138] Ghazavidozein M, Gomis-Bellmunt O, Mancarella P. Simultaneous provision of dynamic active and reactive power response from utility-scale battery energy storage systems in weak grids. IEEE Trans Power Syst 2021.
[139] Kundur P. Power system stability. Power Syst Stab Control 2007.
[140] Farahani HF, Rabiee A, Khalili M. Plug-in electric vehicles as a harmonic compensator into microgrids. J Cleaner Prod 2017;159:388–96.
[141] Monteiro V, Pinto JG, Exposto B, Gonçalves H, Ferreira JaC, Couto C, Afonso JaL. Assessment of a battery charger for electric vehicles with reactive power control. In: IECON 2012-38th annual conference on ieee industrial electronics society. IEEE; 2012, p. 5142–7.
[142] Brivio C, Mandelli S, Merlo M. Battery energy storage system for primary control reserve and energy arbitrage. Sust Energy, Grids and Networks 2016;6:152–65.
[143] Muratori M, Alexander M, Arent D, Bazilian M, Cazzola P, Dede EM, Farrell J, Gearhart C, Greene D, Jenn A, Keyser M, Lipman T, Narumanchi S, Pesaran A, Sioshansi R, Suomalainen E, Tal G, Walkowicz K, Ward J. The rise of electric vehicles—2020 status and future expectations. Progress in Energy 2021;3(2):022002. http://dx.doi.org/10.1088/2516-1083/abe0ad.
[144] Klaes M, Narayan A, Patil AD, Haack J, Lindner M, Rehtanz C, Braun M, Lehnhoff S, de Meer H. State description of cyber-physical energy systems. Energy Informatics 2020;3(Suppl 1):1–19. http://dx.doi.org/10.1186/s42162-020-00119-3.
[145] Gerard H, Rivero Puente EI, Six D. Coordination between transmission and distribution system operators in the electricity sector: A conceptual framework. Utilities Policy 2018;50:40–8. http://dx.doi.org/10.1016/j.jup.2017.09.011.
[146] Schittekatte T, Meeus L. Flexibility markets: Q&a with project pioneers. Utilities Policy 2020;63(August 2019):101017. http://dx.doi.org/10.1016/j.jup.2020.101017.
[147] Daramy-Williams E, Anable J, Grant-Muller S. A systematic review of the evidence on plug-in electric vehicle user experience. Transp Res Part D: Transport and Environment 2019;71(February):22–36. http://dx.doi.org/10.1016/j.trd.2019.01.008.
[148] Oudalov A, Elsaesser D. Could electric vehicles threaten power systems ?. In: tech. rep.. Hitachi ABB Power Grids; 2020.
[149] Calearo L, Marinelli M, Ziras C. A review of data sources for electric vehicle integration studies. Renew Sustain Energy Rev 2021;151(December 2020). http://dx.doi.org/10.1016/j.rser.2021.111518.
[150] Azadfar E, Sreeram V, Harries D. The investigation of the major factors influencing plug-in electric vehicle driving patterns and charging behaviour. Renew Sustain Energy Rev 2015;42:1065–76. http://dx.doi.org/10.1016/j.rser.2014.10.058.
[151] Venegas FG, Petit M, Perez Y. Plug-in behavior of electric vehicles users: Insights from a large-scale trial and impacts for grid integration studies. ETransportation 2021;10:100131. http://dx.doi.org/10.1016/j.etran.2021.100131.
[152] Tsakalidis A, Julea A, Thiel C. The role of infrastructure for electric passenger car uptake in europe. Energies 2019;12(22). http://dx.doi.org/10.3390/en12224348.
[153] Falchetta G, Noussan M. Electric vehicle charging network in europe: An accessibility and deployment trends analysis. Transp Res Part D: Transport and Environment 2021;94(April):102813. http://dx.doi.org/10.1016/j.trd.2021.102813.
[154] Dansk Elbil Alliance. Sådan skaber danmark grøn infrastruktur til én million elbiler. In: tech. rep.. (november):2019, p. 1–36.
[155] Dudek E. The flexibility of domestic electric vehicle charging: The electric nation project. IEEE Power Energy Mag 2021;19(4):16–27. http://dx.doi.org/10.1109/MPE.2021.3072714.
[156] Enexis Netbeheer, Enpuls, ElaadNL, MAXEM. Charge management of electric vehicles at home. (December). 2020.
[157] Bollerslev J, Andersen PB, Jensen TV, Marinelli M, Thingvad A, Calearo L, Weckesser T. Coincidence factors for domestic EV charging from driving and plug-in behavior. IEEE Trans Transp Electr 2021;7782(c):1. http://dx.doi.org/10.1109/tte.2021.3088275.
[158] Jacquemoux D, Terral O, Bollinger L. Electric vehicle charge in collective housing. EVS32 Symposium 2019.
[159] Thingvad A, Andersen PB, Unterluggauer T, Træholt C, Marinelli M. Electrification of personal vehicle travels in cities - quantifying the public charging demand. ETransportation 2021;9:100125. http://dx.doi.org/10.1016/j.etran.2021.100125.
[160] Hecht C, Das S, Bussar C, Sauer DU. Representative, empirical, real-world charging station usage characteristics and data in Germany. ETransportation 2020;6:100079. http://dx.doi.org/10.1016/j.etran.2020.100079.

[161] Hecht C, Victor K, Zurmühlen S, Sauer DU. Electric vehicle route planning using real-world charging infrastructure in Germany. ETransportation 2021;10:100143. http://dx.doi.org/10.1016/j.etran.2021.100143.
[162] Dixon J, Elders I, Bell K. Evaluating the likely temporal variation in electric vehicle charging demand at popular amenities using smartphone locational data. IET Intell Transp Syst 2020;14(6):504–10. http://dx.doi.org/10.1049/iet-its.2019.0351.
[163] Dixon J, Andersen PB, Bell K, Træholt C. On the ease of being green: An investigation of the inconvenience of electric vehicle charging. Appl Energy 2020;258(November 2019):114090. http://dx.doi.org/10.1016/j.apenergy.2019.114090.
[164] Unterluggauer T, Rauma K, Järventausta P, Rehtanz C. Short-term load forecasting at electric vehicle charging sites using a multivariate multi-step long short-term memory: A case study from Finland. IET Electr Syst Transp 2021;(April). http://dx.doi.org/10.1049/els2.12028.
[165] Janjic A, Velimirovic L, Stankovic M, Petrusic A. Commercial electric vehicle fleet scheduling for secondary frequency control. Electr Power Syst Res 2017;147:31–41.
[166] Lee ZJ, Li T, Low SH. Acn-data: Analysis and applications of an open EV charging dataset. In: Proceedings of the tenth acm international conference on future energy systems. 2019, p. 139–49.
[167] Kavianipour M, Fakhrmoosavi F, Singh H, Ghamami M, Zockaie A, Ouyang Y, Jackson R. Electric vehicle fast charging infrastructure planning in urban networks considering daily travel and charging behavior. Transp Res Part D: Transport and Environment 2021;93(March):102769. http://dx.doi.org/10.1016/j.trd.2021.102769.
[168] Kabir ME, Assi C, Alameddine H, Antoun J, Yan J. Demand-aware provisioning of electric vehicles fast charging infrastructure. IEEE Trans Veh Technol 2020;69(7):6952–63.
[169] Dixon J, Bell K. Electric vehicles: battery capacity, charger power, access to charging and the impacts on distribution networks. ETransportation 2020;4:100059.
[170] Canizes B, Soares J, Costa A, Pinto T, Lezama F, Novais P, Vale Z. Electric vehicles' user charging behaviour simulator for a smart city. Energies 2019;12(8):1470.
[171] Al-Hanahi B, Ahmad I, Habibi D, Masoum M. Charging infrastructure for commercial electric vehicles: Challenges and future works. IEEE Access 2021;9:1. http://dx.doi.org/10.1109/access.2021.3108817.
[172] Aboshady F, Pisica I, Axon CJ. Stochastic modeling of vehicle arrival for the UK's first electric vehicle charging forecourt. In: 2021 IEEE power & energy society innovative smart grid technologies conference (ISGT). IEEE; 2021, p. 1–5.
[173] González L, Siavichay E, Espinoza J. Impact of EV fast charging stations on the power distribution network of a latin American intermediate city. Renew Sustain Energy Rev 2019;107:309–18.
[174] Melendez KA, Das TK, Kwon C. Optimal operation of a system of charging hubs and a fleet of shared autonomous electric vehicles. Appl Energy 2020;279:115861.
[175] World Business Council for Sustainable Development. WBCSD Value framework for sustainable charging infrastructure. In: tech. rep..
[176] Global Sustainable Mobility Partnership. Policies for a mature , flourishing & equitable EV charging ecosystem. In: tech. rep.. (November):International ZEV Alliance; 2021, p. 1–60.
[177] Binding C, Gantenbein D, Jansen B, Sundström O, Andersen PB, Marra F, Poulsen B, Træholt C. Electric vehicle fleet integration in the danish EDISON project - a virtual power plant on the island of Bornholm. IEEE PES General Meeting, PES 2010 2010;1–8. http://dx.doi.org/10.1109/PES.2010.5589605.
[178] Marinelli M, Calearo L, Ried S, Pfab X, Cabrera JCD, Spalthoff C, Braun M, Sale H, Torsater BN, Divshali PH, Hanninen S, Ceraolo M, Barsali S, Larsson M, Magdowski A, Gimenez L, Fernandez G. Electric vehicles demonstration projects-an overview across europe. In: UPEC 2020 - 2020 55th international universities power engineering conference, proceedings. 2020, http://dx.doi.org/10.1109/UPEC49904.2020.9209862.
[179] The ACDC (Autonomously Controlled Distributed Chargers) danish research project, https://www.acdc-bornholm.eu/home.
[180] The FUSE (Frederiksberg Urban Smart Electromibility) danish research project, https://danskelbilalliance.dk/fuse.
[181] Sevdari K, Calearo L, Striani S, Rø nnow L, Andersen PB, Marinelli M. Autonomously distributed control of electric vehicle chargers for grid services. In: In: 2021 IEEE PES innovative smart grid technologies Europe (ISGT-Europe).
[182] OctopusEV, InnovateUK. The Powerloop project; https://www.octopusev.com/powerloop.
[183] International Electrotechnical Commission. IEC 61851. 2017, URL https://webstore.iec.ch/publication/33644.
[184] Sevdari K, Striani S, Andersen PB, Marinelli M. Capability assessment and testing of differently controlled EV smart chargers. In: International power electronics conference 2022. 2022, under-review.
[185] Han X, Heussen K, Gehrke O, Bindner HW, Kroposki B. Taxonomy for evaluation of distributed control strategies for distributed energy resources. IEEE Trans Smart Grid 2018;9(5):5185–95. http://dx.doi.org/10.1109/TSG.2017.2682924.
[186] Richardson P, Flynn D, Keane A. Local versus centralized charging strategies for electric vehicles in low voltage distribution systems. IEEE Trans Smart Grid 2012;3(2):1020–8. http://dx.doi.org/10.1109/TSG.2012.2185523.
[187] Stdli S, Crisostomi E, Middleton R, Shorten R. A flexible distributed framework for realising electric and plug-in hybrid vehicle charging policies. Internat J Control 2012;85(8):1130–45. http://dx.doi.org/10.1080/00207179.2012.679970.
[188] Oki Y, Ogawa T, Kawaguchi J. Train power demand control using decentralized and parallel control scheme. IEEJ J Industry Appl 2017;6(6):482–9. http://dx.doi.org/10.1541/ieejjia.6.482.
[189] Lo C-H, Ansari N. Decentralized controls and communications for autonomous distribution networks in smart grid. IEEE Trans Smart Grid 2012;4(1):66–77.
[190] Sevdari K. Electric vehicle chargers market outlook. In: tech. rep. DTU – Technical University of Denmark; 2020.
[191] Lee ZJ, Chang D, Jin C, Lee GS, Lee R, Lee T, Low SH. Large-scale adaptive electric vehicle charging. In: 2018 IEEE Global Conference on Signal and Information Processing, GlobalSIP 2018 - Proceedings. 2019, p. 863–4. http://dx.doi.org/10.1109/GlobalSIP.2018.8646472.
[192] Englberger S, Abo Gamra K, Tepe B, Schreiber M, Jossen A, Hesse H. Electric vehicle multi-use: Optimizing multiple value streams using mobile storage systems in a vehicle-to-grid context. Appl Energy 2021;304(September):117862. http://dx.doi.org/10.1016/j.apenergy.2021.117862.
[193] Tveit MH. Electric Vehicle Charging Flexibility for behind the Meter Applications. MSc in Electrical Engineering, DTU; 2021.
[194] Mwasilu F, Justo JJ, Kim EK, Do TD, Jung JW. Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. Renew Sustain Energy Rev 2014;34:501–16. http://dx.doi.org/10.1016/j.rser.2014.03.031.
[195] Peng C, Zou J, Lian L. Dispatching strategies of electric vehicles participating in frequency regulation on power grid: A review. Renew Sustain Energy Rev 2017;68(July 2016):147–52. http://dx.doi.org/10.1016/j.rser.2016.09.133.
[196] Sortomme E. Combined bidding of regulation and spinning reserves for unidirectional vehicle-to-grid. In: 2012 IEEE PES innovative smart grid technologies, ISGT 2012. IEEE; 2012, p. 1–7. http://dx.doi.org/10.1109/ISGT.2012.6175771.
[197] Sæle H, Petersen I. Electric vehicles in Norway and the potential for demand response. In: 2018 53rd international universities power engineering conference (UPEC). IEEE; 2018, p. 1–6.
[198] Ziras C, Heinrich C, Pertl M, Bindner HW. Experimental flexibility identification of aggregated residential thermal loads using behind-the-meter data. Appl Energy 2019;242(March):1407–21. http://dx.doi.org/10.1016/j.apenergy.2019.03.156.
[199] Palensky P, Dietrich D. Demand side management: Demand response, intelligent energy systems, and smart loads. IEEE Trans Ind Inf 2011;7(3):381–8. http://dx.doi.org/10.1109/TII.2011.2158841.
[200] Knez M, Zevnik GK, Obrecht M. A review of available chargers for electric vehicles: United States of America, European union, and Asia. Renew Sustain Energy Rev 2019;109(March):284–93. http://dx.doi.org/10.1016/j.rser.2019.04.013.
[201] Sachan S, Deb S, Singh SN. Different charging infrastructures along with smart charging strategies for electric vehicles. Sustainable Cities Soc 2020;60(May):102238. http://dx.doi.org/10.1016/j.scs.2020.102238.
[202] Alcaraz C, Lopez J, Wolthusen S. Ocpp protocol: Security threats and challenges. IEEE Trans Smart Grid 2017;8(5):2452–9.
[203] Open Charge Alliance. Open charge point protocol 2.0. 2018.
[204] Schneider Electric. EVlink-electric vehicle charging solutions catalog 2020. 2020.

PAPER [P2]

Autonomously distributed control of electric vehicle chargers for grid services

Authors:

Kristian Sevdari, Lisa Calearo, Simone Striani, Peter Bach Andersen, Mattia Marinelli, Lauge Rønnow

Published in:

Proceedings of the 2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)

DOI:

10.1109/ISGTEurope52324.2021.9640132.

Autonomously Distributed Control of Electric Vehicle Chargers for Grid Services

Kristian Sevdari, Lisa Calearo, Simone Striani,
Peter Bach Andersen, Mattia Marinelli
Department of Electrical Engineering
Technical University of Denmark (DTU)
Roskilde, Denmark
{krisse; lica; sistri; pba; matm}@elektro.dtu.dk

Lauge Rønnow
Circle Consult Research and Development
Circle Consult
Nærum, Denmark
lr@circleconsult.dk

***Abstract*—As part of a sustainable power system, a synergy between electric mobility and renewable energy sources (RESs) can play a crucial role on mitigating the nature of RESs and defer costly grid upgrades via smart-charging. This paper presents a distributed autonomous control architecture for electric vehicle (EV) chargers and a clustering method for charging coordination. The architecture framework is detailed depending on the number of chargers and specific location properties. Moreover, the framework unveils the communication, measurement and power flow. The aforementioned approach aims at simplifying the overall charging experience for the EV owners while coupling it with a healthy grid behavior. The proposed control architecture is simulated on a prosumer case with two EVs. The performance of the controller is considerably affected by observability capabilities of current smart-meters. Faster measurement cycles of smart-meters can reduce the overshoot time span but not prevent it.**

***Index Terms*—distributed control, electric vehicle, smart-charging, flexibility, prosumer**

I. Introduction

As the society is increasing the electricity usage from RESs for its daily needs, the electrical grid experiences the consequences of this transformation. The goal for a sustainable power system showcases a paradigm shift, from generation to demand side control. Based on sustainable grid constraints, ramping flexibility and congestion management are some of the challenges for the future of the grid. To tackle these challenges enabling technologies like utility-scale, behind the meter batteries and EV smart charging are seen as a solution. The common characteristic is the ability to control the load and help demand match supply. Moreover, rapid EV deployment reflects a power delivery that, if left uncontrolled, can result in a concurrent consumption that can potentially overload the grid [1]. Another aspect is the requirement for continuous large residual generation ramping flexibility (MW/min), which increase the costs for running the grid [2]. In this regard unidirectional smart-charging (V1G) becomes crucial for the future reinforcement of the grid, as it unleashes flexibility from EVs to help the grid accommodate a larger energy consumption [3]. Ref. [4] assesses flexibility, which comes as a shift or stretch on time of the charging process and adjustable power consumption. By adjusting charging current, the smart mechanism could further: reduce stress on the grid operation [5]; avoid or delay costly grid upgrades [6]; improve power quality [7]; minimize losses on distribution grid [8]; follow demand response programs [9]; make charging cheaper [10].

A. *Control architecture state-of-the-art*

Smart-chargers as a distributed infrastructure are the meeting point of the energy sector which incorporates the physical grid components and electricity market with the transport sector. Control and coordination of such infrastructure is achieved via centralized, decentralized, or distributed control architectures. Based on a thorough cover of the pros and cons of each method from [11], [12], below it is first compared the centralized versus the decentralized approaches, and afterwards the distributed control, which is also the most promising one towards distributed energy resource (DER) coordination. With the centralized approach the central intelligence, named cloud aggregator, controls all the EVs charging. While with the decentralized technique the intelligence, named virtual aggregator (VA), resides on each charger. Here, even though each charger autonomously runs its controlling actions, decisions of each controller can be influenced by price or a reference control signal from the aggregator, user or utility. The centralized approach is investigated for example in [13], where the aggregated power profile of EVs tracks a reference power resulting from electricity markets. However, the centralized control is quite vulnerable to the VA malfunction, resulting on a need for a backup system. The single server error of centralized control would spread over all chargers. On the contrary, the decentralized control is less sensitive to errors, hence increasing robustness of the system. For what concerns the optimization algorithms, those are easier to be implemented on centralized control, due to the system wide observation, compared to the lack of grid visibility experienced on decentralized control. Ref. [14] compares a charger control on local (decentralized) versus centralized grid measurements. The lack of visibility on local control case, resulted in a slightly lower efficiency compared to the centralized case. In addition, avalanche effects caused by price synchronizations, which is a common challenge for both architectures, should be carefully handled by the controller. In terms of

978-1-6654-4875-8/21/$31.00 ©2021 IEEE

2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe) | 978-1-6654-4875-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ISGTEUROPE52324.2021.9640132

communication protocol, the difference between centralized and decentralized VA control is the two-way (server-clients) versus one-way communication path (Fig. 1). The centralized architecture has a heavy operation in terms of communication and computation when it is scaled-up. On the contrary, the decentralized architecture requires less communication and computation capabilities [15], [16] and diverts data privacy challenges. Moreover, the one-way communication has the potential of implementing plug & play protocols and simplify user interaction [17].

The third approach, distributed control, combines the benefits of centralized and decentralized control. It grows from decentralized control and tackles decentralized lack of visibility and control algorithms integration by introducing a vertical connection with the cloud aggregator [11]. Additionally, it can manifest a control hierarchy, which aligns with the grid physical structure by simplifying and distributing the control objective.

B. Main contributions and charger design

Taking as reference the above mentioned distributed control benefits, this paper proposes a distributed autonomous charging control architecture for providing grid services. To achieve the desired control for the charger, two designs were considered: (i) first, a VA and a dumb charger device separated, where a single VA can control multiple dumb chargers; (ii) second, VA is included in each charger, making it a single device. Here, both charger designs qualify as part of on-board EV charger. From IEC 61851 standard [18], it can adjust its current from 6 to 16 Amps (maximum 11.09 kW) with 1 Amp discrete modulation, as shown at [19]. Currently, the state-of-the-art of smart-charger technology employs the first design, [20] as relevant representatives. A recent initiative of using the second design is followed by Zaptec [21], however with a centralized control approach. On our research the most important aspect of the charger and VA operation is their ability to run autonomously at the largest possible extend. Since the first design is vulnerable of the VA being compromised and losing control of a set of chargers, the second design moved forward and is presented in this manuscript. To tackle the above-mentioned shortcomings of the first charger design, the second design has three pieces:

1) Measurement component: the local grid parameters.
2) Virtual aggregator component: the charger intelligence.
3) Charging component: the protection and charging port.

The rest of the paper is structured as follows. Section II outlines a clustering method for autonomous EV chargers, and presents the autonomous control architecture together with the simulation model. Section III reports the results from the study case and section IV concludes the manuscript.

II. Methodology

The distributed control approach for a scaled-up charger deployment requires to coordinate different actors, namely: market, transmission system operator (TSO), distribution system operator (DSO), cloud aggregator, zonal VA and user. For this reason, the proposed clustering approach and control framework facilitate the interaction between actors.

A. Clustering method

Fig.1 and Table I provide and visualize the clustering method characteristics. Zones cluster chargers based on the number of the EV chargers located behind the same meter and together with the user form the core functioning environment between two actors. Each zone can perform its decision-making for charging operations autonomously, because the cloud aggregator is not vital and does not conflict with local operation goal. However, it helps to perform cross-actor interactions. A short description of each zone follows.

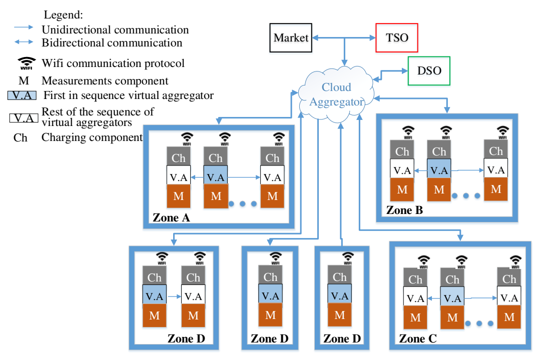


Fig. 1: Visualization of clustering method and communication paths.

TABLE I: Characteristics of the clustering method.

Zone type	Load size	No. of chargers	Independent	Coupled with local load	Type of local load	Coupled with zonal load
A	High	20+	Yes	Yes	Industrial/ Commercial	Yes/No
B	Medium	3-20	Yes	Yes	Industrial/ Commercial/ Residential	Yes/No
C	Low-Medium	3-20	Yes	No	-	Yes/No
D	Low	1-2	Yes	Yes	Commercial/ Residential	Yes/No

Zone A represents a large-size charging infrastructure. This is the case of a parking lot of a stadium, airport, university campus, charging forecourt, etc.. Zone B describes a medium-size charging infrastructure. This can be the parking lot of a school, theater, library, government building etc.. Zone C characterizes a small or medium-size charging infrastructure, dedicated only to charging EVs. Some examples are: public/private parking lots, curbside or garage charging infrastructure. Zone D employs a smaller number of chargers. This zone reflects charging infrastructure of residential houses. In this article, zone D is the case study and it is further explained in Section II-B. Inside the zones, each unit incorporate the same hardware and software, but they have a numbering sequence to specify the order. If the first VA suffers a malfunction, then the second VA replaces its role. By doing so, the leading “token” can be attached to each unit when needed, and provide a robust operation for the zone.

B. Control framework

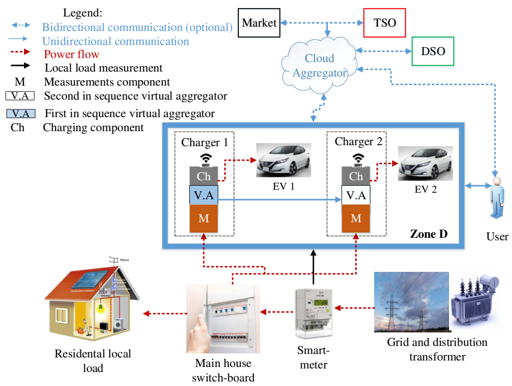


Fig. 2: Autonomous EV charger control architecture for zone D.

Zone D is the typical representation of coupling the consumer or prosumer with the EV charging needs and utility signals. Fig. 2 shows the power flow and information path for the charging operation. The first VA takes care of running the operation in the zone and broadcasts its signal to the nearby VA. The charger takes input signals from the user, the smart-meter and the cloud aggregator. Based on these inputs, the charger decides a charging current for the EV. Depending on the needs and user decision, the charging operation can focus on self-efficiency, time of use tariffs and better utilization of DERs, like rooftop photovoltaic (PV) panels. Furthermore, through the cloud aggregator the charging operation can be part of a bigger picture, coordinated by utility, system operator or market needs. An example for this case is a loading threshold signal, set on the local distribution transformer by the grid operator, limiting the charging current of nearby chargers connected with the transformer. Hence, based on the input signals, different charging modes are offered to the user without compromising his commodity. To summarize, each of these operation modes rely on not harming the grid, as it incentives a behind the meter responsible behavior from the EV user via economic benefits (such as lowering electricity bills, deferring grid upgrades and utilizing local generation). It is relevant to observe that cloud aggregator information regarding market, TSO and DSO controlling actions do not prevent running the local operation, thus in this paper early results regarding local operation are presented.

C. Simulation model

The simulation model representing zone D control framework is displayed in Fig. 3. From left to right, the point of common coupling (PCC) represents the power flow at the smart-meter. The smart-meter measures the active power and transmits this data to the leading VA with a certain measurement delay ($e^{-s\tau 1}$) equal to 1 second. In addition, the meter has a 10 seconds measurement cycle [22]. This limitation affects visibility of fast dynamics in the smart-meter power-flow. Next, VA1 represents the VA in charge, whereas VA2 is the backup option. The VA1 calculates an available power and broadcasts it with a VA processing delay (0.5 second), marked as $e^{-s\tau 2}$. The broadcast of available charging power from VA1 is intended to happen every second to serve even as a time measurement for the backup operation, hence the broadcast delay $e^{-s\tau 4}$. If the following VA does not receive a signal after 3 broadcast cycles (equal to 3 seconds), it will take over the operation. In addition, the charger employes a proportional integral derivative (PID) controller that chooses between 3 sets of PID coefficients based on a priority designed according to state-of-charge (SoC) and user availability (Fig. 3). Here, the initial SoC is required to be manually provided by the user, together with battery capacity [kWh] and expected departure time. In Fig. 3, PD_{i} is the priority coefficient (with a range from 0 to 100), $\mathrm{Userbehavior_i}$ is the available hours (value from 1 to 24) and $\mathrm{SoCout_i}$ is the state-of-charge during charging for EV i. Depending on the values of $\mathrm{PD_i}$ there is: (i) low-priority (LP) when $\mathrm{PD}_i < 33$, (ii) medium-priority (MP) when $33 > \mathrm{PD}_i < 67$ and (iii) high-priority (HP) when $67 > \mathrm{PD}_i$. The last part of the model is the EV part. According to [18], there is a certain delay ($e^{-s\tau 3}$, on average 2 seconds) from the moment the EV receives the signal to start charging and when it reacts to that signal.

To summarize, the control objective is to modulate the output power of each charger, in order to follow a reference demand after receiving the measured demand from the PCC.

III. Results

In this paper early proof of concept results are presented. The simulations are performed for three-phase environment and cover two cases:

1) Case 1: Constant house load (HL) (1.5 kW) and one charger, which goes live with different priorities.
2) Case 2: Constant HL (1.5 kW), first and second charger going live in sequence with three-scenarios on charger priority and charging on local PV production.

A. Case 1

Fig.4 displays a 50 seconds simulation of the Case 1. The charger goes live and starts charging after 10 seconds. Here, it can be noted that once it starts charging, the reference power is activated. The reference demand is 14 kW, reflecting a static maximum desired consumption from the grid. While the 35 Amps grid supply connection allows for a maximum of 24 kW power draw. Moreover, based on the user priority, different charging curves are experienced. The high, medium and low priority need around 16, 32 and 42 seconds each, to reach full charging power (11.09 kW), if there is enough available power. However, due to the smart-meter measurement cycle, the system experiences a lack of measurement visibility at PCC. For that reason, Fig.5 displays the actual and the measured power flow at PCC. Depending on the cycle range, the quality of the control will deteriorate (larger cycle) or improve (smaller cycle). Besides, the available power calculated and broadcasted

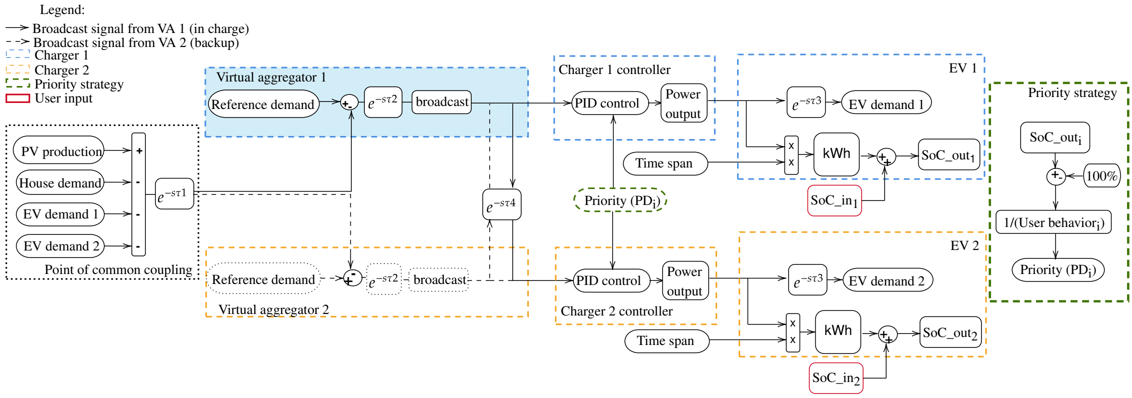


Fig. 3: Simplified simulation model for zone D.

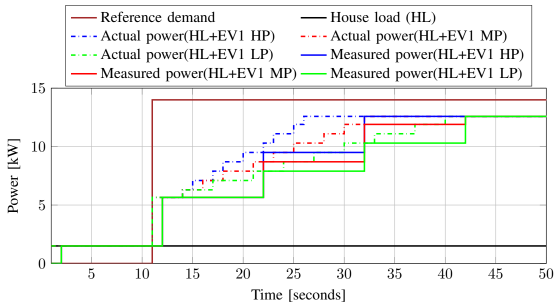


Fig. 4: Case 1: reference demand, house load, actual and measured power at PCC with charger being on high-priority (HP), medium-priority (MP) and low-priority (LP). Actual and measured power differ due to 10 seconds measurement cycle and 1 second delay.

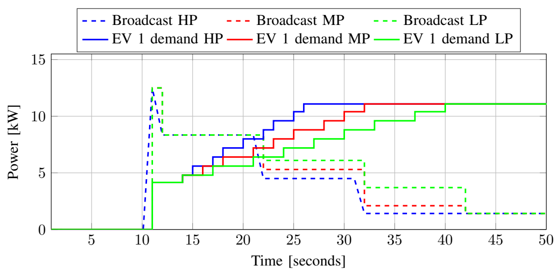


Fig. 5: Case 1: VA broadcast and EV charging power with high-priority (HP), medium-priority (MP) and low-priority (LP).

by VA1 can be distinguished in Fig. 5, together with the charging power delivered for each priority case. The broadcasted power (BP) from Fig.5 and the measured power curves for each scenario from Fig.4, are a mirror of each other. Moreover, after charging power saturates, the VA1 BP displays 1.415 kW (14-1.5-11.09=1.415 kW) power availability. To conclude, the overall system delay counts for 14 seconds, where 10 seconds come from measurement cycle and 4 seconds from the remaining system delays (Fig.4).

B. Case 2

The second case introduces a second charger and a local PV generation (Fig.6). The goal for this case is to charge only with PV generation and for that reason the reference demand is equal to 0 kW. This approach prevents a power flow from the grid. Here, three scenarios are considered: (1) EV1 and EV2 have HP; (2) EV1 has MP and EV2 has HP; (3) EV1 has LP and EV2 has HP. Furthermore, the actual consumption curves reflect the total consumption of the house plus first charger going live after 10 seconds and second charger after 50 seconds with different priorities. Besides, in Fig.6, PV power has negative value reflecting negative power flow (exporting to the grid) at PCC. In Fig.6, for all scenarios at 40-th second the first charger has saturated. The introduction of the second charger with an immediate power step of 4.15 kW (6 A) tests the dynamic response of the controller. Additionally to cyclic measurements, the speed of the PID controller affects the quality of control and the reaction time, hence cannot prevent an overshoot from the reference demand, Fig.7. This is a physical constraint that should be carefully handled by the reference demand assigned to VA or a faster safety logic.

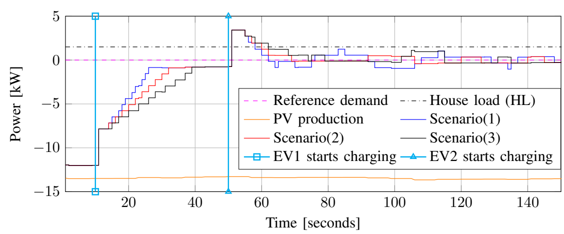


Fig. 6: Case 2: Actual power flow at PCC, scenarios (1),(2) and (3), with local generation and two chargers going live in sequence at 10-th and 50-th second, respectively. Negative power means export, positive means import.

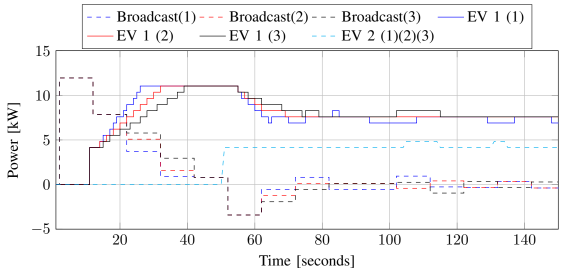


Fig. 7: Case 2: VA power broadcast and EVs charging power with first and second charger going live in sequence at 10-th and 50-th second, respectively. In addition, EVs follow three scenarios (1),(2) and (3).

Here, the overshoot is similar for all scenarios, equal to 3.412 kW. However, the period staying above reference differs. Besides, it is emphasized, the higher the priority the faster the controlling action will compensate. Overshoot spans 14, 19 and 24 seconds for scenario (1),(2) and (3), respectively. Meanwhile, the time period of maximum overshoot stretches equally for all scenarios, 9 seconds. Here, 9 seconds is the worst case and 1 second is the best case, as it reflects the time between two measurements from the smart-meter, depending when the load step happens compared to smart-meter measurement. Moreover, Fig.7 displays the charging power occupied by each charger together with the broadcasted available power. In all scenarios, the second charger occupies the same minimum power (4.15 kW). While, the first charger is the one modulating its power to accommodate the second charger and follow the reference demand.

IV. Conclusion

This paper introduced an autonomous EV charger control architecture with the goal of defining a distributed control architecture. Furthermore, the proposed clustering method facilitates the interaction between actors. The VA is included in each charger, characterizing the charger control with simplicity and scalability implementation. Moreover, the control framework is simulated on a prosumer case. Simulations displayed the quality of the control by evaluating the priority, speed, overshoot margin of the controller, and how it can follow the local PV generation. The overall system delays, the lack of measurement visibility and speed of the controller cannot prevent demand to overshoot the reference. However, the margin of allowed overshoot and implementation of back-up control in order to arrest overshoots will be further investigated on future work.

Acknowledgement

The work in this paper is supported by the research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092).

References

[1] L. Calearo, A. Thingvad, K. Suzuki, and M. Marinelli, "Grid loading due to ev charging profiles based on pseudo-real driving pattern and user behavior," *IEEE Transactions on Transportation Electrification*, vol. 5, pp. 683–694, 2019.

[2] ENTSO-E, "Ten-year network development plan : System dynamic and operational challenges," tech. rep., ENTSO-E, 2020.

[3] J. A. Peças Lopes, F. J. Soares, P. M. Almeida, and M. Moreira Da Silva, "Smart charging strategies for electric vehicles: Enhancing grid performance and maximizing the use of variable renewable energy resources," *24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition 2009, EVS 24*, vol. 4, pp. 2680–2690, 2009.

[4] K. Knezović, M. Marinelli, A. Zecchino, P. B. Andersen, and C. Traeholt, "Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration," *Energy*, vol. 134, pp. 458–468, 2017.

[5] A. Schuller, J. Ilg, and C. Van Dinther, "Benchmarking electric vehicle charging control strategies," *2012 IEEE PES Innovative Smart Grid Technologies, ISGT 2012*, 2012.

[6] C. Crozier, T. Morstyn, and M. McCulloch, "The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems," *Applied Energy*, vol. 268, no. March, p. 114973, 2020.

[7] L. Calearo, A. Thingvad, H. H. Ipsen, and M. Marinelli, "Economic Value and User Remuneration for EV Based Distribution Grid Services," *Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019*, 2019.

[8] E. Sortomme, M. M. Hindi, S. D. MacPherson, and S. S. Venkata, "Coordinated charging of plug-in hybrid electric vehicles to minimize distribution system losses," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 198–205, 2011.

[9] M. H. Albadi and E. F. El-Saadany, "A summary of demand response in electricity markets," *Electric Power Systems Research*, vol. 78, no. 11, pp. 1989–1996, 2008.

[10] J. Dixon, P. B. Andersen, K. Bell, and C. Træholt, "On the ease of being green: An investigation of the inconvenience of electric vehicle charging," *Applied Energy*, vol. 258, no. November 2019, p. 114090, 2020.

[11] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki, "Taxonomy for Evaluation of Distributed Control Strategies for Distributed Energy Resources," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5185–5195, 2018.

[12] J. García-Villalobos, I. Zamora, J. I. San Martín, F. J. Asensio, and V. Aperribay, "Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 717–731, 2014.

[13] A. Di Giorgio, F. Liberati, and S. Canale, "IEC 61851 compliant electric vehicle charging control in smartgrids," *2013 21st Mediterranean Conference on Control and Automation, MED 2013 - Conference Proceedings*, pp. 1329–1335, 2013.

[14] P. Richardson, D. Flynn, and A. Keane, "Local versus centralized charging strategies for electric vehicles in low voltage distribution systems," *IEEE Transactions on Smart Grid*, vol. 3, pp. 1020–1028, 2012.

[15] C. Ziras, A. M. Prostejovsky, H. W. Bindner, and M. Marinelli, "Decentralized and discretized control for storage systems offering primary frequency control," *Electric Power Systems Research*, vol. 177, p. 106000, 2019.

[16] L. Gan, U. Topcu, and S. H. Low, "Optimal decentralized protocol for electric vehicle charging," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 940–951, 2013.

[17] Y. Oki, T. Ogawa, and J. Kawaguchi, "Train power demand control using decentralized and parallel control scheme," *IEEJ Journal of Industry Applications*, vol. 6, no. 6, pp. 482–489, 2017.

[18] International Electrotechnical Commission, "IEC 61851." https://webstore.iec.ch/publication/33644, 2017. Accessed: 26.02.2021.

[19] M. Marinelli, S. Martinenas, K. Knezović, and P. B. Andersen, "Validating a centralized approach to primary frequency control with series-produced electric vehicles," *Journal of Energy Storage*, vol. 7, pp. 63–73, 2016.

[20] L. Calearo, K. Sevdari, and M. Marinelli, "Status e-mobility DK," tech. rep., DTU – Technical University of Denmark, 2021.

[21] K. Sevdari, "Electric Vehicle Chargers Market Outlook," tech. rep., DTU – Technical University of Denmark, 2020.

[22] Aidon, "Han, Interface Deformation." https://www.nek.no/wp-content/uploads/2018/11/Aidon-HAN-Interface-Description-v10A-ID-34331.pdf. Accessed: 26.02.2021.

PAPER [P3]

Barriers and solutions for evs integration in the distribution grid

Authors:

Simone Striani, Kristian Sevdari, Lisa Calearo, Peter Bach Andersen, Mattia Marinelli

Published in:

Proceedings of the 2021 56th International Universities Power Engineering Conference (UPEC)

DOI:

10.1109/UPEC50034.2021.9548235.

Barriers and Solutions for EVs Integration in the Distribution Grid

Simone Striani, Kristian Sevdari, Lisa Calearo, Peter Bach Andersen, Mattia Marinelli
Department of Electrical Engineering
Technical University of Denmark
Roskilde, Denmark
{sistri; krisse; lica; matm; pba}@elektro.dtu.dk

2021 56th International Universities Power Engineering Conference (UPEC) | 978-1-6654-4389-0/21/$31.00 ©2021 IEEE | DOI: 10.1109/UPEC50034.2021.9548235

***Abstract*—The mass penetration of electric vehicles (EVs) could develop grid stability problems due to the increase of peak loads created by coincident charging factors. Smart charging is the control of the EV charging loads and has long been identified as a potential solution. Smart charging could also contribute to grid stability by mitigating the intermittent nature of renewable energy generation. This paper describes the current status of EV flexibility services at the distribution level. The analysis of the smart charging status is done considering the technological, economic and regulatory frameworks, and presenting what the different barriers of each of these aspects are. Additionally, the paper introduces the ACDC project (Autonomously Controlled Distributed Charger), which aims at developing an EV clustering method based on distributed smart charging control logic for flexibility services. For divulgation purposes, the scheduled test case scenario of the parking lot at the Technical University of Denmark is described. The paper concludes on some of the most relevant actions to overcome the most imminent barriers and to push further the roll-out of EV charging infrastructure towards the target EV penetration planned by policymakers.**

***Index Terms*—Electric Vehicle, Distribution Grid, Smart Charging, Flexibility**

I. Introduction

In order to achieve draw-down of CO_2 emissions, the governments are trying to hinder the reliance on fossil fuels for energy production and transportation, in favor of sustainable technologies. On the energy production front, this means promoting renewable energy systems (RES), while regarding the transportation sector, this consists of speeding up the electrification of private and public transportation systems through the roll-out of electric vehicle (EV) technologies. The global scheduled roll-out of EVs aims at reaching 50 million EVs by 2025 and 140 million by 2030 [1]. Charging large EV fleets can result in stability and security challenges in the distribution grid, associated with grid components not being properly dimensioned to stand the resulting increased power required [2]. However, thanks to smart charging, EVs have the potential of adapting their power consumption to the current needs of the distribution grid. The provision of such distribution grid services could delay, or even set aside, the necessity for costly grid updates [3].

Many demonstration projects [4] are currently working on the feasibility of different grid services through smart charging, providing test cases to gain experimental data. EV clusters can be deployed both behind the meter (BTM) and in front of the meter (FTM) [5]. BTM services are services provided to the users and they consist of load coordination among different EVs, buildings (residential, commercial or industrial) and eventual distributed energy resources (DER) at the connection point. FTM services are provided to the Distribution System Operators (DSOs). In this case the EVs can be coordinated in groups by aggregators and provide their flexibility directly to the grid. Smart charging could contribute to the supply adequacy and quality, reduction of peak loads and transformer congestion, reduction of curtailment and allowance for higher usage of low-cost RES electricity [6], [7]. The challenges associated with the integration of EVs in the power system can be categorized in technological, economics, and policy related [8]. The objective of this paper is to identify and list the most relevant challenges in each of these categories, and to conclude by suggesting a set of actions that could be taken for overcoming such obstacles. Furthermore, this paper introduces the ACDC (Autonomously Controlled Distributed Charger) project providing an overview of its demonstration layout.

Firstly, section II provides a conceptual basis including the definition of different EV flexibility services. Secondly, section III describes the status of technological maturity of EV smart chargers. Section IV, provides a description of the economic framework for flexibility while in section V there is a description of the regulatory status of EV infrastructures. Finally, section VI introduces the ACDC project and section VII concludes with some general recommendations deduced from the literature review in each of the described field.

II. Smart Charging as Grid Flexibility Service

This section describes in more details the different smart charging configurations and explains what are the flexibility services. The section ends with a description of the properties of flexibility services useful for the following sections.

A. Smart charging

In Fig.1 the possible smart charging configurations are illustrated. The unidirectional power flow (V1G) chargers allow the car to adjust its rate of charging. Additionally, the vehicle-to-grid (V2G) technology allows to inject power back to the grid. These configurations are FTM because the charger interacts directly with the grid and can be directly controlled by the DSO or aggregator.

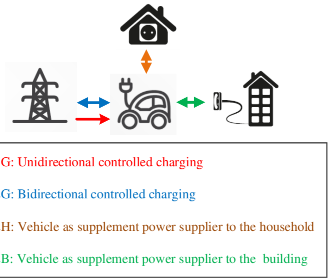


Fig. 1. Illustration of different smart charging configurations adapted from [9].

The other two are vehicle-to-home (V2H) and vehicle-to-building (V2B), both BTM configurations: in these last two configurations the car is connected to a house or a building and it adjusts its consumption to generate services for the household/building (V2H/V2B).

B. Possible flexibility services from EVs

In the power grid, flexibility services are power regulations performed by either supply or demand, with the scope of maximising the security and stability of energy supply. Fig. 2 describes the main services that can be provided with EVs. Such services can be categorized in system flexibility and local flexibility. The first category consists of services that target the system as a whole, including the transmission and the production side of the grid. The local flexibility, which is the main focus of this paper, consists of DSO services (also called FTM services) and BTM services. The DSO services are directly managed and controlled by the DSO through contracts with aggregators or directly with the user. They aim at reducing voltage unbalances (voltage magnitude regulation, phase voltage unbalance reduction), solving the grid instabilities related with the capacity of transformers and lines cables (congestion prevention, capacity management), optimizing the loads to reduce losses (loss reduction) and increase the power quality by active or reactive power injection (power quality correction). Smart chargers available today are still not capable of power quality correction, although studies showed that it could need little development effort and be profitable [10].

BTM services aim at minimizing the electricity cost by importing the least possible energy from the grid and schedule charging at times where the cost of electricity is lower.

In order to clearly define the quantity and the quality of a flexibility service, we follow the definition of theoretical and practical attributes given by the authors in [11]. Theoretical attributes are the attributes that characterize the ideal load modulation set point. Practical attributes are additional attributes introduced due to the unideality of the systems (e.g. delays, tolerances, etc.), and they describe the actual performance with which the charger can follow those set-points. These attributes are described below.

Theoretical Attributes:

- *Direction*: Unidirectional or Bidirectional power adjustment capabilities (V1G or V2G).
- *Power Capacity*: Maximum active power possible.
- *Starting time*: Starting time of the service.
- *Duration*: Duration of the service.
- *Location*: Location of the electric vehicle supply equipment (EVSE) or EV related to the grid topology.

Practical Attributes:

- *Accuracy*: Maximum allowed tolerance between required and delivered power response.
- *Precision*: Maximum allowed tolerance between the power setpoint and the actual power erogation.
- *Activation Time*: Time between setpoint reception and flexibility activation.
- *Ramp-up time*: Time that it takes for the charger to adapt to a higher set-point.
- *Ramp-down time*: Time that it takes for the charger to adapt to a lower set-point.

These attributes need to be assessed to be within standardized tolerances, and to be transparently communicated among the stakeholders for the provision of flexibility services. Such communication is crucial for the establishment of quality and therefore value of the different products provided.

III. Current Technology and Infrastructures

A. Electric Vehicle Supply Equipment

Nowadays smart charging technologies have reached market roll-out in Europe. The overview of the commercially available chargers carried out in [12] concludes that, in 2020, more than 50% of the available EVSE presented smart charging functionalities. The most common functionalities reported in the paper are load modulation (dynamic load management and limitation of power set-points) and power sharing with the household/building. Here, some of the capabilities of the top-end smart chargers available today are described:

- *BTM functionalities*: These capabilities refer to the ability to coordinate the charging between the vehicles and the household/building demand and eventual DER production. The charging can be coordinated via power sharing, scheduling and charging prioritization (using state-of-charge (SOC), driving plan or pattern).
- *Inter-connectivity*: In order to provide the above-mentioned distribution services and BTM functionalities, smart chargers are able to have multiple communication channels: they are connected locally with the building energy meter, but also they are connected to the internet, from which they could be coordinated by aggregators in order to provide flexibility. Moreover, their status is usually available via the internet or Bluetooth so that the user can interact remotely with the EV, the charger and easily plan his trip.
- *System recognition*: ID number of the individual EVSE, or alternatively of the EV, must be defined to ensure that the proper user is procured and remunerated for the delivered flexibility. Further information

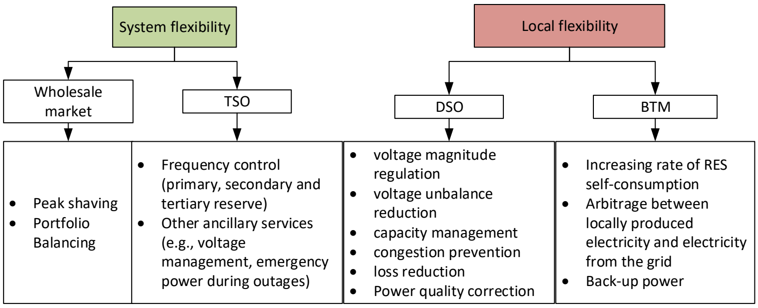


Fig. 2. Description of the different flexibility services that EVs can provide.

should also be made accessible by the EV manufacturers, which is, e.g., currently not the case for the SOC data. Naturally, user privacy must be ensured by regulations so that all collected data are treated as confidential and kept private.

It is important to notice that the capabilities listed describe the top-end chargers available, and therefore the characteristics are not representative of the average of the chargers in the market and even less of the chargers currently deployed. Indeed the majority of the chargers in European cities are not capable of any smart function, thus also called ”dumb” chargers.

B. Control architecture

The coordination and control of different clusters of smart chargers need to be performed effectively by the DSO, user or aggregator. Different control architectures have been proposed and investigated in the literature [13]. They can be categorized into centralized, decentralized or distributed control architectures. The centralized architectures rely on a central intelligence called Cloud Aggregator (CA), which controls directly all the chargers. In the decentralized approach, the intelligence is called Virtual Aggregator (VA). The VA resides in each charger and is therefore sensitive to local measurements. Since the centralized control relies on a single server, it is prone to disconnection errors and delays. On the other hand, the decentralized system is very robust, although its controlling capacity is less efficient due to the limited data it receives from the system. Finally, the distributed control approach combines the benefits from both architectures. It is able to coordinate between local control and global control because it communicates both with VA and CA.

C. Grid observability and smart metering

One of the most important factors in the prompt development of charging infrastructures is the development of smart metering and grid observability. Direct measurements from EVSE or other local metering systems could provide the DSO with more knowledge about the grid, making it capable of judging if flexibility procurement or grid reinforcement are necessary.

Countries where the adoption of smart chargers is combined with experimental demonstration campaigns are leading the way towards the generation of invaluable lessons on user behaviours, the correct planning of charging infrastructures as well as economic and policies suggestion for aggregators, DSOs and governments [14].

In the majority of the countries where smart meters are deployed, all units are certified and installed by the DSO, which is also responsible for data collection and management.

It is of particular importance to clearly define the requirements on the specific measurement parameters, such as the sampling rate, which must be chosen as a trade-off between the information speed on the one hand, and the installation and data management cost on the other.

The European Clean Energy Act requires that all member states assess the cost-benefit of smart meters and ensure that at least 80% of consumers are equipped with smart meters by 2024, if the cost-benefit analysis is positive [15]. It is also stated that smart meters functionalities should include remote reading with two-way communication and a sampling rate not greater than 15-min. Yet, there are no international standards that would ensure these functionalities, so the status across Europe considerably varies.

However, several European countries have plans for a wide-scale roll-out of smart meters supported by the national regulatory framework. Yet, there is still a relatively large share of countries that has not started their deployment due to negative or inconclusive results of the cost-benefit analysis [2].

As a result, many of the consumers still buy ”dumb chargers” because they are cheaper and countries do not incentivize the purchase of smart options. The additional cost of retrofitting the older EVSEs once EV smart charging becomes a common practice should be considered.

The EV chargers and models need to show their internal parameters to DSOs and aggregators to be managed correctly in the flexibility service. There is still a lack of experimental data on the practical attributes of the EV capabilities, and authors in [16] state that there might be a difference in EVs response accuracy based on the external conditions.

Smart meters characteristics and functions need to be standardized as their varying performances is observed to be one of the major barriers towards flexibility procurement.

D. Information and communication technologies

Information and communication technology (ICT) ensures advanced metering, control and transactional communication among different stakeholders: EVs, EVSEs, DSOs, TSOs, market operators/players and the end-user. ICTs are crucial to provide grid monitoring for the actual research and development of flexibility services. EV-related communication protocols can be divided into front-end and back-end protocols, and they are respectively between the EV and EVSE and between the EVSE and a third party, such as an aggregator. Nowadays, the vast majority of contemporary EVs are compliant with IEC 61851 or SAE J1772 standard, according to which the EV charging current can be limited between the minimum charging current of 6 A and the maximum one, which is the EVSE rated current (10 A, 16 A, 32 A, etc.). One of the present limits of the existing protocols is the lack of communication of fundamental EV information, such as battery size and SOC. Moreover, there are not protocols that support entirely V2G functions. Standard ISO/IEC 15118 covers communication between EVSE and EV, as well as among all stakeholders involved in the supply process [17]. It takes into account the data encryption for both confidentiality and data integrity purposes and it is currently being revised to include V2G functionalities if used together with OCCP 2.0 or IEC 63110 (between EVSE and aggregator or charge point operator).

IV. Economic framework for flexibility

The economic framework for flexibility services is a central barrier hindering the development of a flexibility value chain. The economic and regulatory frameworks are hugely interconnected. This section will illustrate different economic tools currently under development for creating flexibility value on the DSO perspective that are proposed by the literature [18].

A. Grid codes

This approach proposes to update grid codes for grid connection of flexible loads or DER with the scope of imposing flexibility requirements. There are discussions on what should be strategical requirements to facilitate the development of market-based flexibility services.

B. Connection agreements

These are agreements between DSOs and consumers for flexibility provision. There are two main types of smart connection contracts: interruptible contracts and variable capacity contracts (VCCs) [8]. Interruptible contracts entitle the DSOs to control EV charging energy consumption based on the grid conditions. This type maximizes grid stability at the expense of user comfort and acceptance. In VCCs, the DSOs provide scheduled or dynamic max power allowance for charging necessities and related dynamic prices.

C. Electricity tariffs

This mechanism generates an indirect provision of flexibility because it encourages end-users to adapt their consumption. Network tariffs are paid by the consumers, together with other taxes. They consist of roughly 25% of the electricity bill and resemble the planning and operational costs of the network. There are different kinds of tariff structures/components: energy component (€/kWh), capacity component (€/kW), grid connection component (€). Currently, not all countries are deploying network tariffs to encourage the use of flexibility. Although some of the above-mentioned tariffs are still under development, every country should update the electricity tariff to include at least two components: the capacity and an energy one [11].

The ToU (Time-of-Use) tariff is a simple price mechanism to incentivize off-peak consumption that could result in reduced congestion. However, with high-penetration scenarios the charging synchronization of large fleets during off-peak hours is a potential risk.

A tariff structure trending in current research is the Distribution Locational Marginal Prices (DLMPs), where the cost of electricity is dependent on the particular nodes of the distribution grid. There are different variations of such tariff, which can include local constraints such as voltage, losses, power quality, etc. These structures, although promising, raise some important concerns regarding the difficulty of implementation as well as inequality and transparency issues.

Dynamic capacity tariffs could be a very efficient framework. These tariffs would force consumers to adapt their maximum consumption to the grid conditions for a given period of time. The drawbacks of the capacity tariffs are that they could hinder the development of fast-charging stations.

D. Flexibility markets

In recent years some markets for different EV flexibility services were developed (for example, system balancing and energy management) and started being used by aggregators. EV flexibility markets at the distribution level are still far from sufficient, since there is not a market structure and digital infrastructure [19]. Regulators should incentivize the creation of a larger number of smaller local flexibility markets based on nodal pricing systems [20]. With a Market-based approach, DSOs explicitly procure flexibility services from a market. The penetration of the EV-based services in flexibility markets will increase the value of such services and allow their trading among different stakeholders. Again, there are various viable approaches: Long or Medium-term bilateral contracts or short terms Market Platforms. The role of the DSO is to define the flexibility requirements, which can be offered by different aggregators or prosumers.

Market frameworks have a strong potential to generate value for all stakeholders [21] and are the preferred approach by regulators.

V. Regulation

A. Redefining the role of DSOs

Before the beginning of the transition towards renewable energy resources the grid was easier to operate. This is because it had a virtually radial shape with the consumers at the center and the producers at the outer radiuses. The flow was unidirectional and the loads and production were easier to forecast and control. Therefore the DSO approach to congestion and voltage issues was simply reinforcing the grid when needed (the so-called "fit-and-forget" approach). The economic and regulatory frameworks were therefore built around this model and the DSOs were remunerated based on the capital expenditures (CAPEX) for grid renovation.

Nowadays, the evolution towards smart grids requires a shift towards a TOTEX-based (total expenditure) framework, where the DSOs need to minimize their OPEX (operational expenditure) as well as the CAPEX. This need is at the moment only partially met and there is still need for a reform of the regulatory framework to push the DSOs to manage their expenditures proactively and to deploy the value of load flexibility [22].

B. *Standardization of EV connections*

Because of its technological novelty, there are often some administrative problems related to V2G technology. In more details, V2G chargers installation imply additional and often redundant administrative procedures that discourage their adoption by the user. The cause of these obstacles is that connection requirements, classification and standardization of V2G connections are not fully developed yet. Regulators, system operators, EV and EVSE manufacturers need to work on the standardization of interconnection requirements in order to reduce the administrative processes and ensure safety for both end-user and the system itself. On the other hand, V1G, V2H and V2B are more technologically mature and their connections have already been standardized in the previous years [17].

C. *Interaction between actors*

As previously stated, there are different approaches for DSOs to provide flexibility: Grid codes based, contract based and market based approaches. The grid codes based approach requires the DSOs to stipulate direct obligations for flexibility provisions or contract arrangements directly with the EV user so that they can directly control the EV charging process. The market-based approaches require an additional interaction between DSOs and TSO. The interaction between DSOs and EV users often requires the mediation of aggregators, which can cluster different EVs and manage their flexibility into tradeable services packages.

The interaction between DSOs and TSOs is considered a key aspect in the European Clean Energy Package as the penetration of RES and DER increases. This is because the distribution network and the transmission network often have different needs that could be in contrast. Often the needs of the transmission network need to be prioritized compared to the ones of the distribution network.

VI. The ACDC Project

Some of the aspects discussed in this paper are analysed by the ACDC project. The ACDC (Autonomously Controlled Distributed Charger) is a Danish project that aims at developing a clustering method for autonomous smart charging with distributed control architecture and a virtual aggregator. The cluster contains a set of EV chargers controlled to provide FTM and BTM grid services. The global grid status is communicated via a Cloud Aggregator, through which FTM services can be provided. Furthermore, the local coordination between the chargers for BTM services is handled by the virtual aggregator. The development of the clustering method is ongoing, although a more detailed description of the control logic is available in [23] together with the simulation results of a V2H scenario with 2 EVs. As part of the demonstration campaign, the designed technology will be installed in one of the parking lots of the Risø research campus of the Danish Technical University (DTU). A satellite picture of the parking lot is shown in Fig. 3. The scope is to validate the charging performances in a V2B office case. The parking lot will host 8 smart chargers with 2 type-2 plugs each. Each plug can support a maximum charge rate of 11 kW from a 3 phase charger. The parking lot could potentially charge with a max power of 88 kW. However, the grid capacity of the parking is limited to 43 kW (63 A, 3 phase). The parking lot will serve to develop and demonstrate ACDC's distributed charging control logic for BTM and FTM services under limited grid capacity.

Fig. 3. Satellite picture of the parking lot location. The red dots indicate the chargers.

VII. Conclusion

An overview of the current development status of the EV integration in the distribution grid was provided. Many authors believe that smart chargers could potentially be an important component of the future smart grid. Smart charging could drastically reduce the drawbacks related to EV integration and, at the same time, solve the increasing grid instability problems due to other sources, like DER. However, there are still many barriers before the smart charging technology is fully mature. In this paper, the authors described the current status of EV flexibility services at the distribution level, including the technological, economic and regulation perspectives. Moreover, the

TABLE I

FUTURE STEPS NEEDED TO PUSH THE DEVELOPMENT OF ROBUST EV INFRASTRUCTURES FOR DISTRIBUTION GRID SERVICES IN EACH OF THE FIELDS ANALYZED

Technical	**Economic framework**	**Regulatory framework**
Further R&D on smart charging capabilities.	Keep or introduce temporary incentives for cars, shared mobility and Mobility-as-a-service	Enhance active management requirement to DSOs
Standardize and ensure interoperability between different EVs and EVSE.	Research on business models for aggregators and charge point operators	Standardize cost-benefit analysis for smart meters
Develop and test ICT and standards (especially V2G)	Develop and test new Network tariff structures	Ensure a clear classification and standardization of V2G connection requirements for V2G prosumers
User interactivity and interconnectivity	Strategical location for different types of chargers to ensure trust in EV infrastructures investors	Create incentives for smart chargers purchase
Continue the demonstration project campaigns to gather data.	Establish local flexibility platforms with increasingly competitive approaches.	Define DSO-TSO priorities and the interaction between every stakeholder
Increase grid observability	Continuous revision and improvement of economic framework of flexibility based on the lessons learned	Set ambitious targets (CO_2 reduction, targets for different transport types)

authors introduced the ACDC project and a test case of its demonstration campaign to explain part of the ongoing research and development on clustering methods for smart charging functionalities. In conclusion, recommendations on possible steps to be followed in each of the analyzed perspectives are summarized in table I: From a technical point of view, the bottleneck for the roll-out of smart charging is the related ICT: Development of the existing standards and protocols is needed to ensure EVSE-EV interoperability, user-EVSE interactivity and grid observability. From an economic point of view, the focus should be on two aspects: developing market platforms to provide trading of services and developing business models to assure profitability for investors of EV infrastructures, as well as aggregators and prosumers. Finally, the regulatory framework should set ambitious targets and stimulate technical and economic value-chain development. This can be done by standardizing and including the different technologies, defining their available products and regulating the interaction between stakeholders along the value chain.

ACKNOWLEDGMENT

The work in this paper is supported by the research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092).

REFERENCES

[1] International Energy Agency, "Global ev outlook: Entering the decade of electric drive," tech. rep., 2020.

[2] K. Knezović, M. Marinelli, A. Zecchino, P. B. Andersen, and C. Traeholt, "Supporting involvement of electric vehicles in distribution grids: Lowering the barriers for a proactive integration," *Energy*, vol. 134, pp. 458–468, 2017.

[3] L. Calearo, A. Thingvad, H. H. Ipsen, and M. Marinelli, "Economic value and user remuneration for ev based distribution grid services," *Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019*, 9 2019.

[4] M. Marinelli et al., "Electric vehicles demonstration projects-an overview across europe," *UPEC 2020 - 2020 55th International Universities Power Engineering Conference, Proceedings*, 9 2020.

[5] International Renewable Energy Agency, "Behind-the-meter batteries: innovation landscape brief," tech. rep., 2019.

[6] P. Hanemann, M. Behnert, and T. Bruckner, "Effects of electric vehicle charging strategies on the german power system," *Applied Energy*, vol. 203, pp. 608–622, 2017.

[7] M. V. D. Berg, I. Lampropoulos, and T. AlSkaif, "Impact of electric vehicles charging demand on distribution transformers in an office area and determination of flexibility potential," *Sustainable Energy, Grids and Networks*, vol. 26, p. 100452, 2021.

[8] F. G. Venegas, M. Petit, and Y. Perez, "Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services," *Renewable and Sustainable Energy Reviews*, vol. 145, p. 111060, 7 2021.

[9] The International Renewable Energy Agency, "Innovation outlook: Smart charging for electric vehicles," tech. rep., 2019.

[10] S. Martinenas, K. Knezovic, and M. Marinelli, "Management of power quality issues in low voltage networks using electric vehicles: Experimental validation," *IEEE Transactions on Power Delivery*, vol. 32, pp. 971–979, 4 2017.

[11] K. Knezović, M. Marinelli, P. Codani, and Y. Perez, "Distribution grid services and flexibility provision by electric vehicles: A review of options," *Proceedings of the Universities Power Engineering Conference*, vol. 2015-November, 2015.

[12] K. Sevdari, "Electric vehicle chagers market outlook," tech. rep., 2020.

[13] X. Han et al., "Taxonomy for Evaluation of Distributed Control Strategies for Distributed Energy Resources," *IEEE Transactions on Smart Grid*, 2018.

[14] C. Hecht, S. Das, C. Bussar, and D. U. Sauer, "Representative, empirical, real-world charging station usage characteristics and data in germany," *eTransportation*, vol. 6, 11 2020.

[15] European commission, "Regulation (eu) 2019/943 on the internal market for electricity," 2019.

[16] K. Knezovic, S. Martinenas, P. B. Andersen, A. Zecchino, and M. Marinelli, "Enhancing the role of electric vehicles in the power grid: Field validation of multiple ancillary services," *IEEE Transactions on Transportation Electrification*, vol. 3, pp. 201–209, 3 2017.

[17] H. S. Das, M. M. Rahman, S. Li, and C. W. Tan, "Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review," *Renewable and Sustainable Energy Reviews*, vol. 120, 3 2020.

[18] Council of European Energy Regulators, "Flexibility use at distribution level," tech. rep., 2017.

[19] T. Pallesen and P. H. Jacobsen, "Solving infrastructural concerns through a market reorganization: A case study of a danish smart grid demonstration," *Energy Research and Social Science*, vol. 41, pp. 80–88, 7 2018.

[20] J. Ostergaard et al., "Energy security through demand-side flexibility: The case of denmark," *IEEE Power and Energy Magazine*, vol. 19, pp. 46–55, 3 2021.

[21] A. Gadea, M. Marinelli, and A. Zecchino, "A market framework for enabling electric vehicles flexibility procurement at the distribution level considering grid constraints," *20th Power Systems Computation Conference, PSCC 2018*, 8 2018.

[22] Transport & Environment, "How implementing the clean energy package can foster electromobility," tech. rep., 2020.

[23] K. Sevdari, L. Calearo, S. Striani, L. Rønnow, P. B. Andersen, and M. Marinelli, "Autonomously distributed control of electric vehicle chargers for grid services," 2021, under-review.

PAPER [P4]

Experimental Validation of Onboard Electric Vehicle Chargers to Improve the Efficiency of Smart Charging Operation

Authors:

Kristian Sevdari, Lisa Calearo, Bjørn Harald Bakken, Peter Bach Andersen, Mattia Marinelli

Published in:

Sustainable Energy Technologies and Assessments

DOI:

10.1016/j.seta.2023.1035124.

Sustainable Energy Technologies and Assessments 60 (2023) 103512

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Experimental validation of onboard electric vehicle chargers to improve the efficiency of smart charging operation

Kristian Sevdari [a,*], Lisa Calearo [b], Bjørn Harald Bakken [c], Peter Bach Andersen [a], Mattia Marinelli [a]

[a] Department of Wind and Energy Systems, Technical University of Denmark, Frederiksborgvej 399, Building 330, 4000 Roskilde, Denmark
[b] Ramboll Danmark A/S, Hannemanns Allé 53, 2300 Copenhagen, Denmark
[c] Department of Market Design and System Utilization, Statnett, Nydalen Allé 33, 0484 Oslo, Norway

ARTICLE INFO

Keywords:
Efficiency
Electric vehicles
Onboard charger
Smart charging
Transport sustainability

ABSTRACT

Electric vehicles (EVs) are at the center of the power and transport sector coupling; however, smart charging is required to not compromise the integrity of the grid. In this work, we propose, test, and validate a method for investigating EV onboard chargers via the OBDII port. We present the charging efficiency and reactive power characteristics of 38 different EV models from the last 11 years. Data show that, due to added losses, smart charging through current modulation can increase global charging energy demand from 1%–10%. In addition, 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. Our projections show an efficiency of 88%–95% by 2030 and a saturation between 90%–96% by 2035. Therefore, the newly presented AC-to-DC conversion efficiency values help achieve better results when calculating life cycle assessment, grid integration and energy simulation that consider EVs. Curtailed smart charging can further integrate charging needs by implementing phase balancing and matching with behind-the-meter local generation. Finally, our results urge regulators and automakers to further improve charging technology and legislation based on other technological experiences, e.g. solar inverters.

Introduction

An increased penetration of EVs can reduce a large portion of CO2 emissions when coupled with renewable energy sources (RES)[1]. On the one hand, RES suffer from intermittency, which requires a flexibility source to cover their absence or abundance. On the other hand, EVs are parked most of the time, making their charging patterns an attractive source of flexibility [2,3]. However, concurrent charging or more specifically instantaneous power can compromise grid integrity [4] and reduce power quality [5].

Smart charging aims at making EVs an asset for the grid [6]. Benefits can be observed in higher EV penetration levels [7], fewer investments in grid upgrades [8,9], greater utilization of RES and charging infrastructure [10], and higher economic benefits for end users [11].

However, smart charging faces both technical barriers, e.g., grid observability [12], battery degradation [13,14], charging technology [15], cyber security [16], and market barriers, e.g., value framework [17], data privacy [18], interoperability [19], transparency and fairness [20].

Furthermore, smart chargers require a higher investment cost compared to dumb chargers [21]. Second, the avalanche and rebound effects due to market synchronization could amplify the instantaneous power challenge rather than solve it [22,23]. Third, according to [24], the energy costs are 46%–54% of the levelized cost of electric vehicle charging in Europe. Furthermore, due to industrial privacy, commercial OBCs efficiency is an area that has barely been investigated [25].

We investigate mode 2–3 OBC from IEC61851 (charging from 6–32 Amps) [26] in combination with Type 2 plug, which are widespread technologies [26,27]. This investigation is of paramount importance to understand the sustainability and energy efficiency of EVs as a mode of transport [28]. In the charging scheme, OBC is between the vehicle's AC charging plug and battery management system (BMS).

Furthermore, the authors of [29] predicted that the nominal efficiency of commercial of OBC would be 97% by 2020 and 98% by 2025. Previously, the authors of [30] presented their 22 kW modular OBC technology, in which the efficiency numbers are between 85% and 94%. The contradiction in such a predicted efficiency value increases when General Motors data display 93% [31], and the authors of [25,27] suggest that the efficiency of OBC should be in the range of 94%–96%.

* Corresponding author.
E-mail addresses: krisse@dtu.dk (K. Sevdari), licl@ramboll.com (L. Calearo), Bjorn.Bakken@Statnett.no (B.H. Bakken), petb@dtu.dk (P.B. Andersen), matm@dtu.dk (M. Marinelli).

https://doi.org/10.1016/j.seta.2023.103512
Received 20 June 2023; Received in revised form 28 September 2023; Accepted 16 October 2023

A literature review highlights the lack of tested AC-to-DC conversion efficiency values for EVs OBC [32,33], albeit the most energy-intensive load in the household. Such conversion efficiency values from AC to DC are critical for the EV optimal large and small-scale management charging strategies [34], life cycle assessment [35] and understanding the global energy implications of charging demand [36].

The knowledge gap is even recognized by the European Commission (EU) for their European efficiency labeling regulation [37,38]. The European efficiency label has been successful in helping consumers make better decisions and reducing European energy needs [39]. We explore this research gap by proposing an investigation method based on vehicle on-board diagnostics port (OBDII) and conducting an extensive test campaign for OBCs of 38 commercial vehicle models. The objective is to answer four research questions.

- Are BMS data reliable across different manufacturers?
- What are the energy conversion efficiency, PF and reactive power curves of commercial OBCs? And does the information change between automakers?
- How has OBC technology evolved and what can we expect in 2030?
- For three-phase OBCs, how do they behave compared to single-phase charging?

The charging efficiency is an important factor when calculating the EV total cost of ownership [40]. Therefore, the investigation in this article is vital on the consumer protection front. Second, it is important for charging point operators (CPOs), aggregators and EV owners due to the direct impact on their economy and business models. Third, maintaining the required PF values is essential for grid operators to not compromise the quality of supply and for regulators to be able to govern the deployment of technology. Consequently, charger manufacturers must follow the guidelines and provide the user with a manual on how to use their chargers according to the regulations. Furthermore, the proposed setup to read the data from BMS via an OBDII dongle has the potential to drastically facilitate future diagnostics of EVs. Thus, such an investigation has the potential to bridge the data visibility gap of EVs and commercially use it to highlight the best charging efficiency and reactive power consumption.

The remainder of the paper is structured as follows. Section ”Methodology” describes the methodology of the research and the tools used to conduct the investigation campaign. Further, Section ”Investigation campaign results” presents the results from a global to local approach. In addition, it provides a comprehensive overview and future predictions for EVs charging characteristics. Finally, Section “Conclusions” concludes the article with the main findings.

Methodology

Measurement and data acquisition setup

Depending on their design, OBCs are built as standalone units. The OBC converts the AC charging current from the grid to the equivalent DC current required by the battery management system (BMS) to supply the lithium-ion battery. We built two modular EV laboratories, as shown in Fig. 1. The objective is twofold: first, to determine the AC-to-DC power conversion efficiency of the OBC, and second, to measure the rest of the grid side parameters (such as reactive power and power factor). Four main parameters are measured/derived for each vehicle:

1. Active power [kW] consumed from the grid.
2. Reactive power [kVAr] consumed from the grid.
3. Apparent power [kVA] consumed from the grid.
4. DC active power [kW] on the battery side of the vehicle after AC-to-DC conversion.

The OBC stands between the vehicle’s Type 2 AC plug and the BMS-DC battery pack. On the one hand, finding the reactive power and power factor curves is straightforward by measuring the AC side consumption values with a DEIF multimeter (Fig. 1a). On the other hand, the principle behind the AC-to-DC conversion efficiency compares the charging measurements from the DEIF multimeter (grid-side data) with those from the vehicle’s internal DC battery side (BMS-side data).

Furthermore, most EVs, in Europe, do not charge more than 32 Amp AC [15]. Thus, from left to right in Fig. 1(a), the laboratory requires a 32 Amp three-phase supply from the grid side (Labcell). This supply is done through a CEE 32 Amp plug that connects the Labcell and the smart charger; see Fig. 1(a). Between the grid side and the smart charger, a DEIF multimeter is located to measure electrical parameters on the grid side. Such measurements are transmitted via the DTU cloud and stored on the operator’s computer. The smart charger is the central piece of this investigation, as it allows for the manipulation of the charging current in order to characterize the operational values of OBC.

The connection between the smart charger and the EV is achieved through a Type 2 cable. Type 2 cable is responsible for delivering energy and control signals to EV. Therefore, it has seven pins indicating phases 1,2 and 3, earth, neutral, proximity pilot, and control pilot [41]. The control pilot is the communication path for the pulse width modulation (PWM) signal, which controls the charging process.

The purpose of the operator’s test sequence is to compare the charging data on the grid side with the BMS side. DEIF multimer measures grid-side data, and BMS data are recorded through the OBDII port. BMS records data on the DC side; thus, after AC-to-DC conversion is performed. A smart charger is necessary to investigate the full spectrum (from minimum to maximum current) of the OBC. The operator, see Fig. 1(b) can control the vehicle OBC charger by providing the desired charging current limit in Amps. This numerical value is translated by the smart charger to a duty cycle value for the PWM; see Fig. 1(b).

$$I_{ch} = \mathrm{D} \times 0.6 \text{ Amps} \quad (1)$$

where I_{ch} is the charging current, D is the duty cycle, and 0.6 Amp is the charging current step [42]. The BMS reads the allowed duty cycle through the control pilot of the Type 2 plug. In combination with the OBC, it draws the required current from the grid; see Fig. 1(b).

It is important to mention that the OBC is located between the AC plug and the BMS and we intend to explore the knowledge that the BMS offers. There are two important components inside the OBC. The AC-to-DC converter converts the AC charging current to the DC equivalent. The DC voltage output is designed for the 400 or 800 V battery pack architecture. Another component is located after the AC/DC converter, which is the DC/DC converter. The role of the DC/DC converter is to supply the 12 V battery, the auxiliaries, and the electronic control unit (ECU) [43].

In general, the data on the BMS side can be extracted from the OBDII that is located on the driver side. BMS communicates to the OBDII via the CANBUS communication [44]. The internal vehicle computer and BMS converge their data sets at OBDII. Here, an OBDII dongle is used to read the data through a phone app via Bluetooth. The proposed method, OBDII data readings, does not require components to be disassembled from EV, and has previously been utilized for battery degradation matters in [45]. The article showed that OBDII is successful in understanding battery degradation of Nissan-brand vehicles. However, our methodology proposes that OBDII can be used to evaluate the characteristics of all commercial OBC. We extended the research work to 14 automakers and 38 vehicle models released in a window of 11 years.

To verify that such BMS readings are accurate, one can compare the OBDII values when the vehicle is fast charging (DC charging). This is because with DC chargers, the OBC is bypassed and the current goes directly to the BMS/DC battery. Consequently, the values observed on the fast charger (outside of the vehicle) should be the same (or very close to as there can still be some cable losses) as the values coming

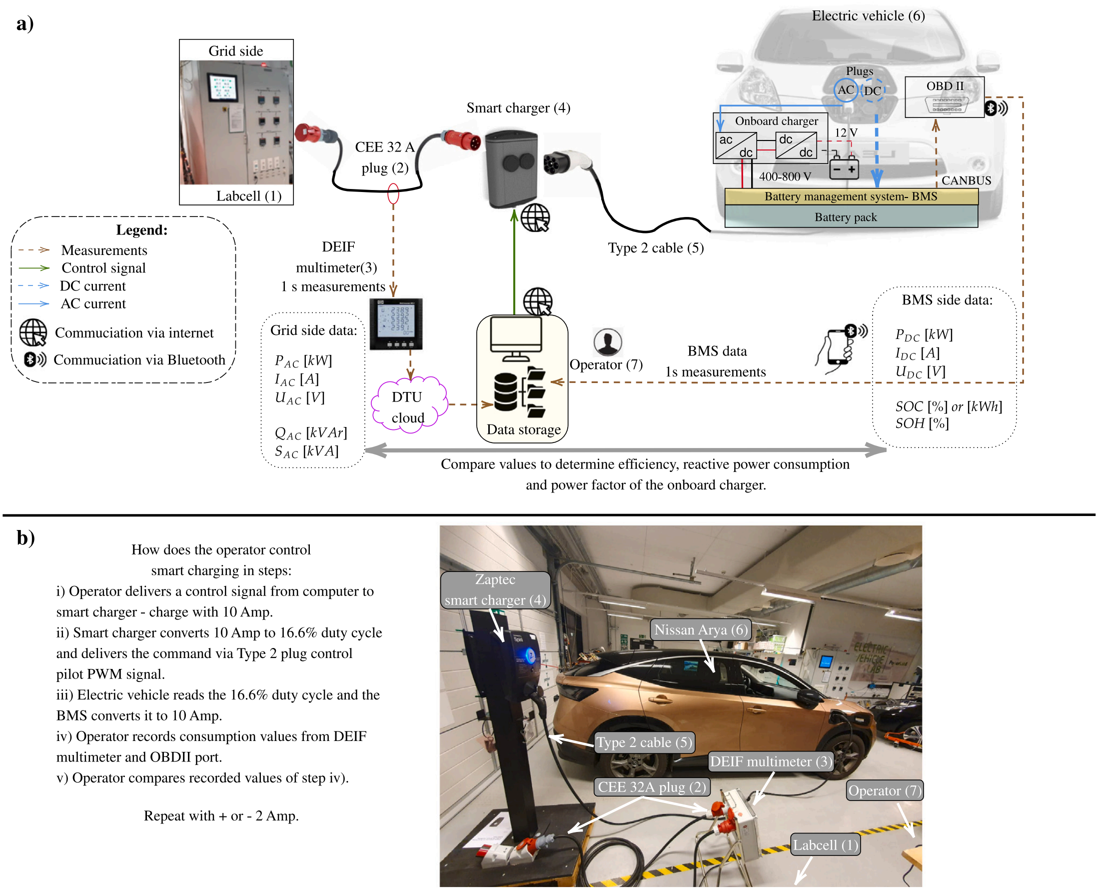


Fig. 1. (a) Overview of the methodology and tools used for the testing campaign. (b) Physical setup representing the method.

from the BMS through the OBDII port. This article, in addition to expanding the work from [43] to multiple vehicle brands, highlights the benefits and challenges of such an approach. For example, a single app cannot read the information from all vehicles. Therefore, in the following section, we present the devices used to collect data from the different models.

Testing campaign tools

In order to have a complete view of light-duty vehicles, we investigated 38 vehicles, from early EVs that have a Type 1 plug (such as Nissan LEAF from 2012 and Peugeot iOn from 2011) to the latest models (such as Tesla Model Y, Kia EV6, etc.) that commonly use a Type 2 plug for their AC charging process. Previously, Fig. 1(b) displayed the physical location where the laboratory is built for the testing campaign. One can observe that the laboratory is modular and does not rely on a specific smart charger.

Similarly, the Type 2 cable is used at all times, even though some older vehicles do not support it. 38 vehicles from production years 2011 to 2022 are tested. Two of such old vehicles have a Type 1 plug instead of the common Type 2 plug. In that case, to make such a plug transition (from Type 2 to Type 1) for the charging cable, we have designed and built a plug converter from Type 2-to-Type 1. To check the physical plug converter device please see Fig. A.1(b) in the Appendix. The Type 2 plug remains connected to the smart charger, while the Type 1 plug connects to the vehicle. To read the vehicle DC side data (battery side) from BMS, an OBDII dongle is required. The dongle communicates via Bluetooth to an app on the smartphone. To check the screenshots of apps please see Fig. A.1(a) in the Appendix.

The DC side data include the displayed state-of-charge (state-of-charge (SOC)) [%], state-of-health (SoH) [%], battery energy content [kWh] at the moment, charging power [kW] and the DC current [A] and voltage [V] during charging. By reviewing different apps, it was found that the Car Scanner app [46] can serve most vehicles; whereas the LeafSpy app [47] is more specific for Nissan LEAF models and the scan my tesla app [48] is the only one compatible for Tesla models. In addition to the app and OBDII dongle for Tesla models, an OBDII adapter is needed [48]. Lastly, for Volvo and Polestar, it was not possible to read DC-side data due to encrypted OBDII port readings. For such vehicles, the article discusses only the data on the AC side. Finally, for a complete overview of the tools used for each automaker please check Table A.1 in the Appendix.

Performance indicators and testing sequence

The test procedure is designed with the aim of harmonizing EV testing by defining key performance indicators (KPI). Such KPIs are as follows:

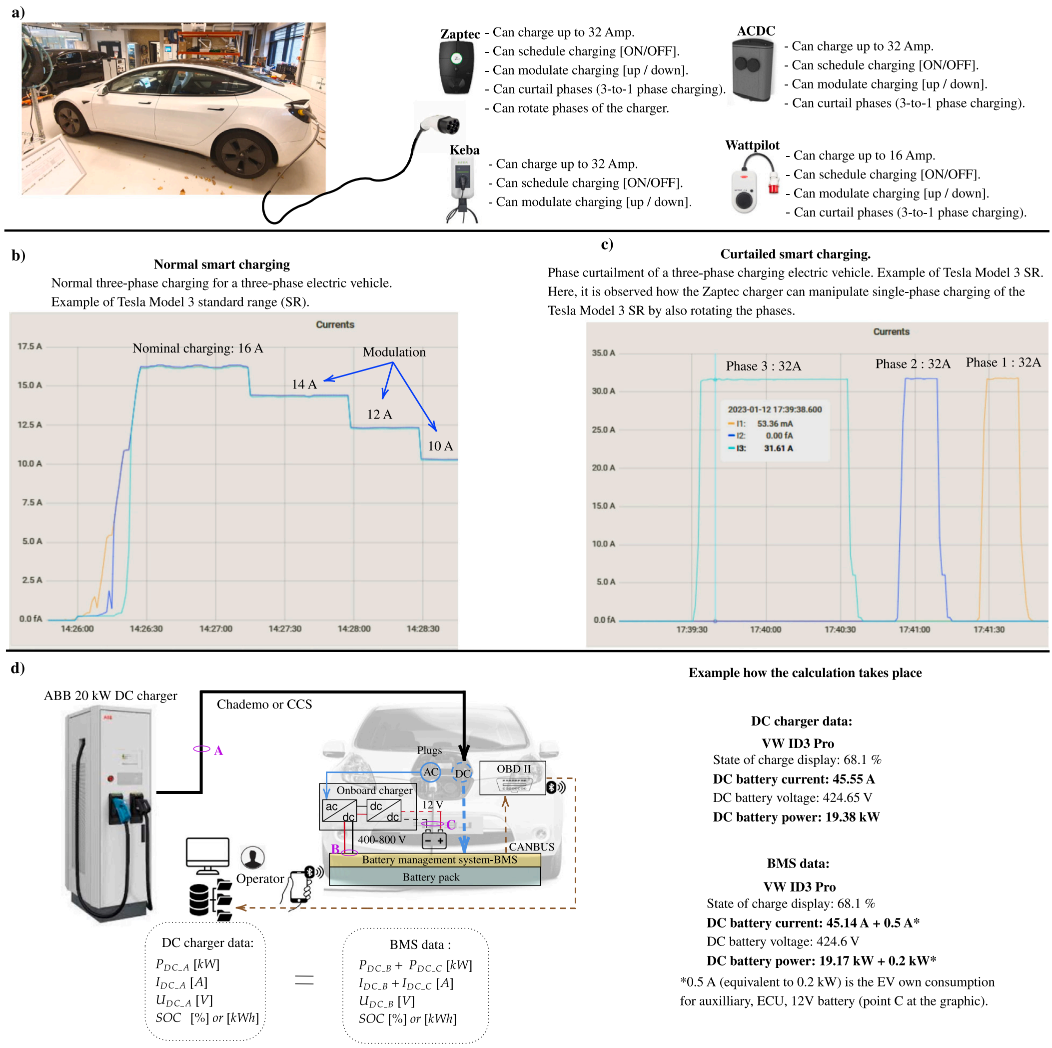


Fig. 2. (a) State-of-the-art of smart chargers and corresponding characteristics. Screenshots of the Grafana measurement interface of the DEIF multimeter during (b) three-phase charging and (c) curtailed charging of the Tesla Model 3 SR. (d) The approach followed to verify the BMS readings on the DC charger side.

- Maximum and minimum charging power.
- Maximum and minimum recorded efficiency.
- Maximum and minimum recorded power factor.
- Maximum and minimum recorded reactive power.

To quantify such KPIs, we charge EVs by controlling the PWM signal of the smart charger. First, EV is charged with the maximum charging current (16 or 32 A) and later is reduced by 2 Amps every 30 s until the minimum charging current (6 A) is reached. The opposite is performed to complete a cycle of down- and up-modulation. Such a testing cycle is performed twice, below and above 50% SOC to investigate whether SOC affects the KPIs. In addition, to better understand possible patterns, the KPIs are combined with the necessary metadata for each vehicle, such as the year of production, the price, the size of the battery, the state of health (SOH), the voltage of the battery system and the charging phases.

Smart charging and OBDII data reliability

The testing campaign encompasses all types of OBC, including single-phase, two-phase, and three-phase. Furthermore, the fleet being tested ranges from production years 2011 to 2022, providing a rare opportunity to compare the OBCs included by automakers in their commercial EVs. The IEC 61851 standard [42] allows charging between 6–51 Amp. However, AC smart chargers by accordingly changing the duty cycle can deliver 6 to 32 Amp per phase [15]. For that reason, we built the EV testing laboratory to analyze the entire charging spectrum of EVs and to handle up to 32 Amp per phase (Fig. 1). Previously, a definition for the smart charger has been proposed in [15] from which we provide an adjusted version in the following: *Smart charger is an electric device providing protection, communication, at least scheduling and at most modulation, phase curtailment (3 to 1-phase switch) and phase switching for the EV charging process.*

Fig. 2(a) explains the characteristics of the smart chargers and, together with parts (b) and (c), displays how a Tesla Model 3 standard range charges in normal smart charging and curtailed smart charging mode.

Smart charging can be achieved by all smart chargers. However, there exists a special case, curtailed smart charging, for EVs that have a three-phase OBC, which is called phase curtailment. Phase curtailing means that a three-phase EV can charge in a single phase by curtailing two of the phases. It should be mentioned that the first phase should always remain energized [49]. Recognizing such technological development, it is necessary to characterize not only normal smart charging, but also curtailed smart charging. To avoid relying on data from a single charger, four state-of-the-art smart chargers are used to further investigate normal and curtailed smart charging.

More specifically, Fig. 2(b) presents how the Tesla charger reacts to the nominal three-phase 16 Amps charging and how modulation occurs to lower charging currents part of the testing sequence. Additionally, Fig. 2(c) demonstrates the ability to switch the 16 Amp three-phase charging of the Tesla Model 3 to a single phase 32 Amp. When switching the Tesla charging from 3-to-1 phase, one can notice that OBC can deliver up to 32 Amp compared to 16 Amp. This feature is investigated for different brands.

In addition, Fig. 2(c) reveals a state-of-the-art attribute of the Zaptec smart charger, the ability to rotate the charging phases. Lastly, each charger was tested to measure its own power consumption, resulting in the following values: Keba 12 Watt, Zaptec 8 Watt, ACDC 10 Watt and Wattpilot 9 Watt. These values are deducted from each test case accordingly.

EVs typically have two charging ports for AC and DC charging, respectively. The AC port connects to OBC and BMS to charge the battery pack, as shown in Fig. 2(d). The DC port connects directly to the battery pack. This design allows verification of the reliability of BMS data, such as SOC, current, voltage, and power of the DC battery. To confirm the accuracy of the BMS data, EV can be charged with a DC charger, bypassing OBC and any potential losses associated with OBC. By doing so, the readings from BMS should match the current and voltage measured on the DC charger, as shown in Fig. 2(d).

Measurements at point A (see Fig. 2 (d)) are compared with the sum of measurements at points B and C. The comparison allows us to determine the quality of BMS data. Point A represents the charging data from the DC charger outside or off-board the vehicle. Point B represents the charging data that flows to the DC battery pack. Point C accounts for the auxiliary energy data that the vehicle is consuming for its own operation. On average, tested EVs consume 150–350 watts for their internal normal operation when on or awake.

This procedure is used for each vehicle model tested, using an ABB 20 kW DC charger. BMS data can also be accessed through the OBDII port and viewed on applications. In our tests, the difference between ABB DC charger readings and BMS data was negligible (4–10 Watt).

Investigation campaign results

Global view

The results reflect the average values of the test for the vehicle in a controlled temperature environment. Four test cycles are conducted per vehicle, two when SOC was less than 50% and two when SOC was greater than 50%. However, before presenting any result, the measurement error range should be highlighted. For example, the AC-to-DC conversion efficiency, hereafter referred to as efficiency, suffers from 2%–3% uncertainty at 6 Amps and is linearly reduced to 0.2–0.5% at 32 Amps. The reason for such a difference is the embedded losses in OBC power electronics [50,51]. Their size remains almost constant during the charging current range. Nevertheless, the losses-to-charging current ratio is higher on lower charging currents and significantly lower on higher charging currents. Finally, the reactive and apparent power measurements are affected only by the quality of the DEIF multimeter (class 0.1) [52].

Fig. 3 shows a parabolic efficiency pattern during normal smart charging for three-phase vehicles. As mentioned above, this is explained by the losses-to-charging current ratio in different current ranges.

The values reflect normal smart charging for three-phase vehicles. The position of vehicles on the heat map is randomly chosen. The coloring label for AC-to-DC conversion efficiency is capped from 65%–95% to provide a clear view of the evolution of efficiency over the years and brands. However, it should be mentioned that Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2020, 2021), and Nissan Townstar (2022) have 0% efficiency at 6 Amps charging current, thus, a darker color.

The results show a gradual improvement in efficiency from 2011 to 2022 in all charging current values. The same model from the same automaker displays different efficiency curves, depending on the year of production. Consequently, one can observe the versions of Peugeot e-208 (2020 and 2022), Renault Zoe ZE50 R110 (2020 and 2021), or Nissan LEAF e+ (2019 and 2022). In addition, if the vehicle model is from the same year and the same original equipment manufacturer (OEM), the efficiency curve is very similar; see VW e-golf (2017 x2) in Fig. 3.

Furthermore, PF is the ratio of active power to apparent power. It indicates the efficiency of the electrical power usage. A PF of 1 means that all the power supplied is being used to do useful work, while a PF of less than 1 indicates that some of the power is being wasted. Consequently, a lower PF can be caused by inductive loads (e.g. electric motors), reactive power, and nonlinear loads (e.g. electronic equipment). The legend of the PF heat map, in Fig. 3, is restricted from 0.9 to 1, as required by the EU Commission Regulation 2016/1388 for the connection of demand to the low-voltage grid [53].

The PF values are being improved with newer models, where the majority are close to unity PF. Data suggest a correlation between lower PF values and higher reactive power consumption. During charging on low currents, some models violate the regulation for connection of demand to the low-voltage grid. Additionally, some models consume a large amount of reactive power. Thus, the regulation regarding such large reactive power consumption needs to be re-addressed as it threatens the integrity of the low-voltage grid. Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2019, 2020), and Nissan Townstar (2022) have a PF lower than 0.9 for currents less than 14 Amps, so these vehicles are colored black. Such specific models experience a 0 PF at 6 Amps. Similarly to the efficiency in Fig. 3, there is a different behavior for the same model produced in different years by the same automaker. For example, the Peugeot e-208 (2020 and 2022), Renault Zoe ZE50 R110 (2020 and 2021), and Nissan LEAF e+ (2019 and 2022) versions have different PF behavior across the same charging current. However, the same model produced in the same year by the same automaker (2017 VW e-golf) experiences the same PF behavior.

In addition, the reactive power consumption for each model is introduced in Fig. 3. The data show six clusters of reactive power consumption curves. The majority of EVs from early to the latest models consume reactive power in the range of 200–700 VAr, following a similar curve as Polestar 2 Long Range Dual-Motor (LRDM) (cluster 1). This means that reactive power consumption reduces when the charging current increases. The opposite is true for the Tesla Model S P90D (400 V battery architecture) and the Kia EV6 LR (800 V battery architecture), representing clusters 2 and 3 respectively. Consequently, this is not a feature of a specific battery voltage architecture (400 or 800 V), as it can be found on both architectures.

Hyundai Kona is representative of cluster 4. Such a cluster experiences an almost complete parabolic pattern, where the highest reactive power consumption is in the middle charging current range (10–12 Amps). Tesla Models 3/Y represent cluster 5, which are very close to 0 VAr reactive power consumption. Lastly, an outlier of reactive power consumption are those EVs that employ an OBC similar to the Renault Chameleon/Zoe [27] (cluster 6). That is, the case of an integrated OBC with the electric motor [27]. The rest, clusters 1–5, represent behaviors of dedicated OBC, which are the majority in the automotive industry.

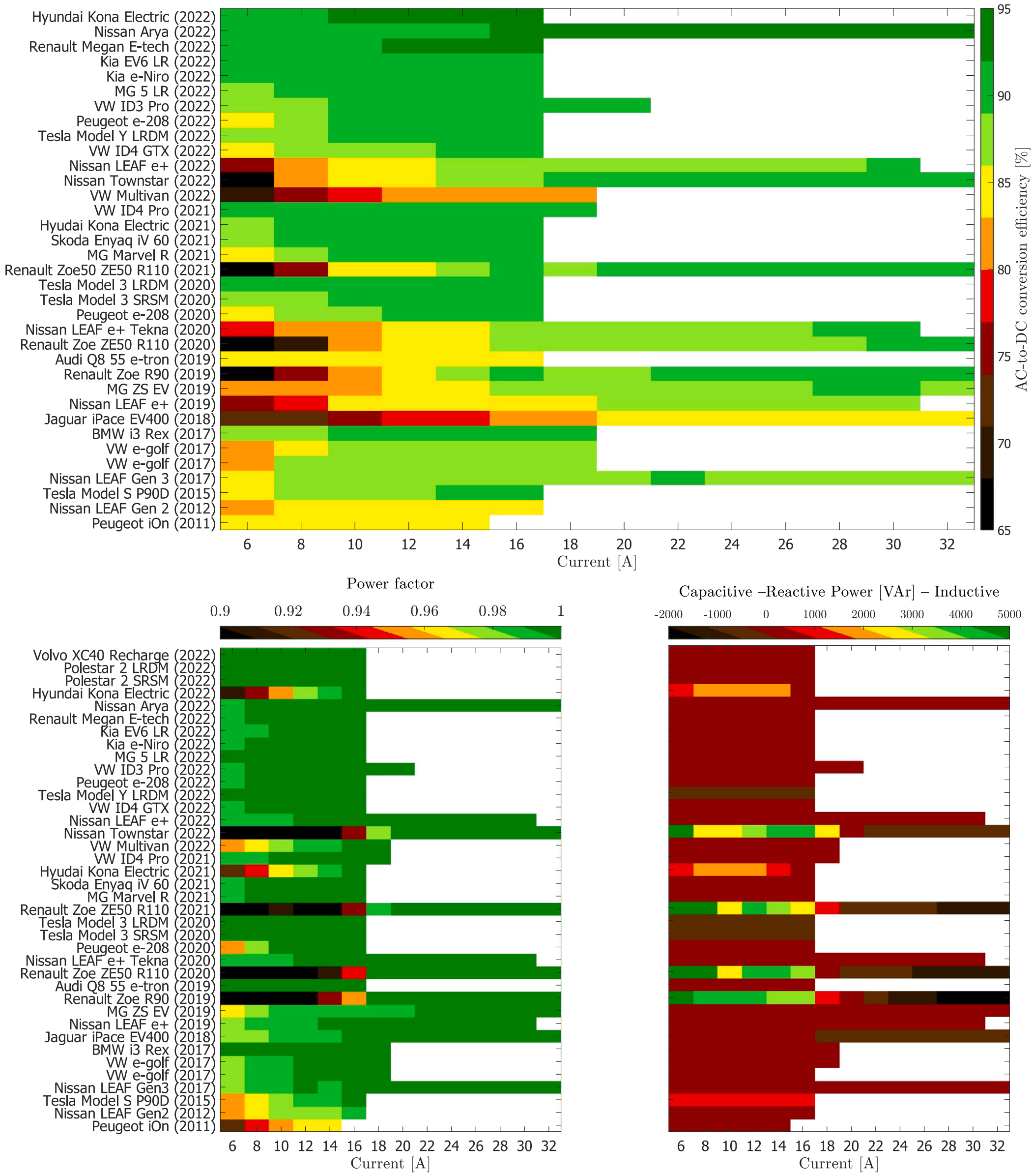


Fig. 3. EV OBC characteristics (up) AC-to-DC conversion efficiency, (down-left) PF, and (down-right) reactive power consumption from 2011 to 2022.

Current and future OBC performance conundrum

When looking for trends in the behavior of OBC, the vehicle SOC is an important variable. Figs. 4(a–d) show that the SOC state does not affect the efficiency of OBC or the reactive power consumption. This outcome confirms that SOC affects only the size of the charging current requested by OBC. For example, a charging current of 10 Amps has the same efficiency and reactive power consumption at low (i.e. 40%) and high (i.e. 92%) SOC.

Moreover, Figs. 4(e, f) show the three most efficient OBC models and the three most grid-friendly vehicles, out of 38 vehicle models over 11 years. The former is diverse in automakers, while the latter is dominated by Tesla. The concept of grid-friendly means that it is almost neutral to reactive power consumption during all charging currents.

In Figs. 4(g, h) historical efficiency data are plotted alongside a second-order fitted function. The OBC maximum efficiency has progressed over the years; however, for 2022 it averages the efficiency of 90%, while the OBC minimum efficiency is around 83%. Based on 11 years of data, a second-order polynomial prediction of efficiency is displayed up to 2040. The prediction considers a conservative approach in which the technology will develop at a faster rate until it saturates at a 96% efficiency value in 2035. These saturation levels for the development of OBC efficiency agree with historical developments in solar inverters, which are a good example of technological progress [54].

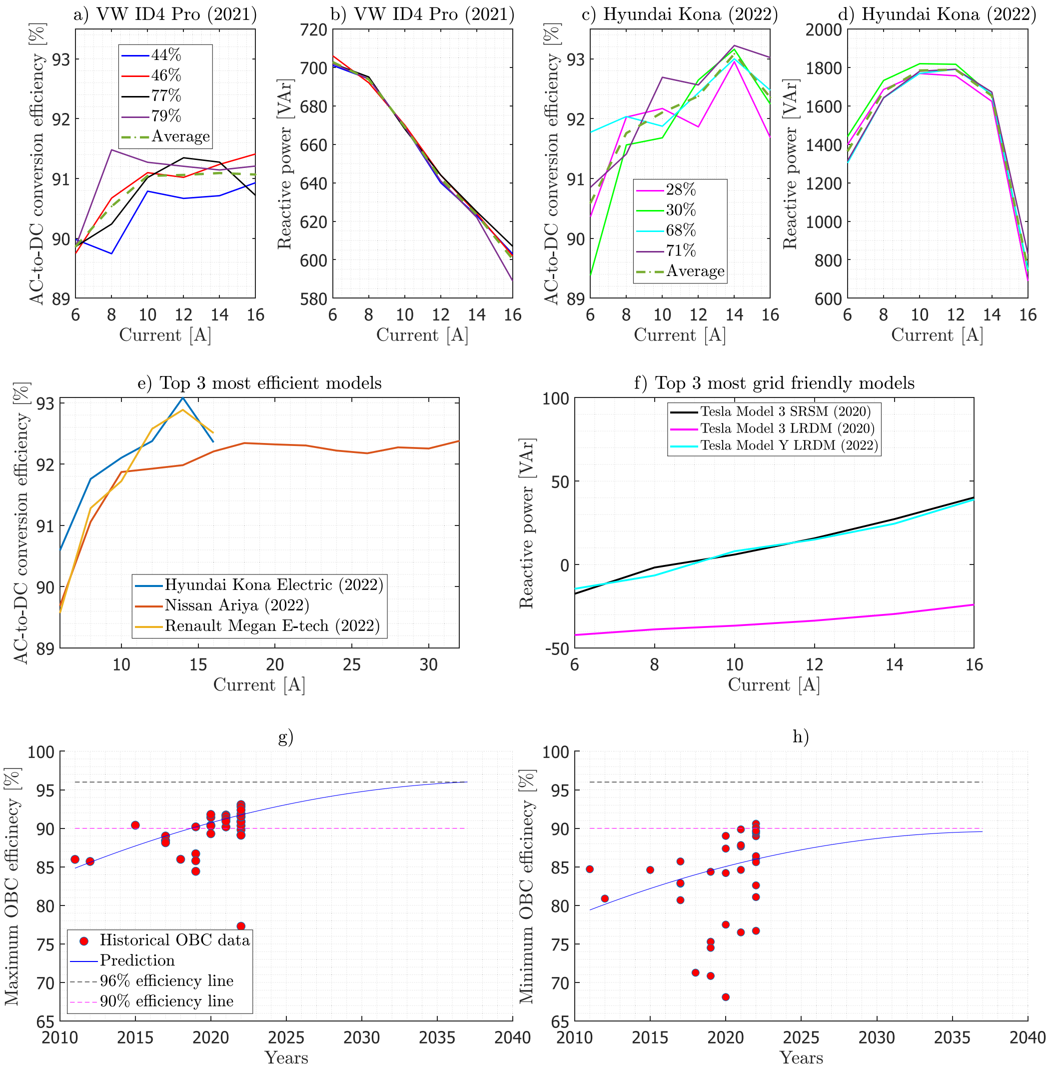


Fig. 4. Charging efficiency and reactive power consumption curves under different SOC for ID4 Pro (2021) (a, b); Hyundai Kona Electric (2022) (c, d). The three best performing models in (e) efficiency and (f) reactive power. Evolution of (g) max and (h) min OBC AC-to-DC conversion efficiency.

Therefore, only by 2030 could it be possible to reach a maximum OBC efficiency of 95% as a market average product. Similarly, by 2030 it could be possible to support a value of 88% for the minimum efficiency of OBC and a saturation of efficiency of 90% in 2035. The data suggest that the fleet of EVs varies considerably in its efficiency values. This uncertainty complicates the optimization of EVs; therefore, it needs to be addressed with technological improvements.

Finally, the results of the test campaign are summarized in Table 1 with respect to four key performance indicators (KPI) (charging power, recorded efficiency, PF, and reactive power) and the official automakers' data.

Furthermore, 9 of 38 (9/38) are single-phase models. Two are two-phase models and 27/38 are three-phase models. Three models have a Type 1 plug, while the rest have a Type 2 plug. Similarly, the combined charging system (CCS) plug dominates (30/38), while the Chademo plug is found in 5/38 models. The EV battery architecture can be 400 or 800 V. Of the vehicles tested, only one has 800 V architecture (Kia EV6 LR) according to data from [55].

The data set is more diverse when you look at the price and battery size range. Prices can be clustered into three groups: 30–45k Euro, 46–65k Euro, and 66–120k Euro. Although the nominal battery size ranges from 16–95 kWh, with 50 to 75 kWh being the most common sizes.

Table 1 highlights the charging current recorded versus official values. According to the IEC 61851-1 standard, between 10%–85% duty cycle the vehicle should draw between 6–51 Amps. However, the maximum charging current is subject to limitations, and 32 Amps is the industry norm.

Consequently, there is a mismatch between the automakers' official Min and Max charging current values with those recorded from the test campaign. The mismatch is smaller for the min values and significant for the max values. For example, Nissan Arya consumes 5.88–32.1 Amps while the official numbers are 6–32 A Amps. The measurement equipment is class 0.1. The majority of vehicles suffer from higher

Table 1
Results from the nominal testing of the investigated fleet. Ranking is done randomly according to the production year. Green highlights three models that perform best in their respective categories. The price values and nominal battery capacity are taken from [55].

No	Year	OEM	Model	Variant	Original price [Euro]	Plug type AC/DC	Nominal capacity [kWh]	Ch. phases	Official max/min ch. current	Tested max/min ch. current	Max ch. power [kW]	Min ch. power [kW]	Max efficiency [%]	Min efficiency [%]	Max reactive power [VAr]	Min reactive power [VAr]	Max power factor [%]	Min power factor [%]
1	2011	Peugeot	iOn		29k	Type 1/Chademo	16	1	16/6	13.65/6	3.16	1.26	85.97	84.7	218	147	96.9	92.6
2	2012	Nissan	LEAF	Gen 2	32k	Type 1/Chademo	24	1	16/6	16.6/6	3.82	1.36	85.7	80.88	541	332	98.2	95.7
3	2015	Tesla	Model S	P90D	120k	Type 2/CCS	90	3	16/6	15.5/5.2	10.83	3.55	90.4	84.5	1468	861	99.2	95.2
4	2017	Nissan	LEAF	Gen 3	33k	Type 1/Chademo	40	1	32/6	31.5/6	6.9	1.41	89	85.7	323	190	99.8	97.7
5	2017	VW	e-golf		32k	Type 2/CCS	36	2	16/6	16/6	7.23	2.62	88.39	82.82	644	454	99.4	97.5
6	2017	VW	e-golf		32k	Type 2/CCS	36	2	16/6	16/6	7.14	2.6	88.43	82.9	644	455	99.4	97.5
7	2017	BMW	i3	Rex	37k	Type 2/CCS	33.2	3	16/6	16/6	10.9	4.04	88.13	80.68	292	176	99.7	99.1
8	2018	Jaguar	iPace	EV400	76k	Type 2/CCS	90	1	32/6	31.5/6	7.26	1.41	85.98	71.27	196	−60	99.6	97.3
9	2019	Nissan	LEAF	e+	37k	Type 2/Chademo	62	1	32/6	30/6	6.75	1.34	87.42	75.28	293	176	99.7	97.2
10	2019	MG	ZS EV	Standard	34k	Type 2/CCS	51,1	1	32/6	32.11/5.77	7	1.22	86.7	70.85	393	211	99.5	96.8
11	2019	Renault	Zoe	R 90	34k	Type 2/-	44.1	3	32/6	32/7	22.08	0	90.19	0	4300	−1870	99.7	0
12	2019	Audi	e-tron	Q8 55	80k	Type 2/CCS	95	3	16/6	15.9/6	11.07	4.07	85.79	84.36	548	507	99.8	99.1
13	2020	Renault	Zoe	ZE50 R110	37k	Type 2/-	54.7	3	32/6	30.4/7.5	20.68	0	90.4	0	4563	−976	99.8	0
14	2020	Tesla	Model 3	Standard range Single Motor	53k	Type 2/CCS	60	3	16/6	16.4/6	11.59	4.39	91.42	87.37	40	-18	99.9	99.9
15	2020	Tesla	Model 3	Long range Dual Motor	62k	Type 2/CCS	78.1	3	16/6	16.3/6	11.63	4.39	91.8	89.02	-24	-42	99.9	99.9
16	2020	Peugeot	e-208		35k	Type 2/CCS	50	3	16/6	15/6	10.05	3.98	90.3	84.2	400	200	99.5	96
17	2020	Nissan	LEAF	e+ Tekna	41k	Type 2/Chademo	62	1	32/6	30/6	6.66	1.35	89.3	77.5	422	192	99.7	98
18	2021	Renault	Zoe	ZE50 R110	37k	Type 2/-	54.7	3	32/6	32/7	19.6	3.08	91.73	0	4615	−800	99.9	0
19	2021	Hyundai	Kona	Electric	43k	Type 2/CCS	67.5	3	16/6	15.7/6	10.69	3.38	91.6	87.65	1650	701	99.6	92.3
20	2021	Skoda	Enyaq	iV 60	42k	Type 2/CCS	62	3	16/6	16/6	10.93	4.16	90.18	87.82	643	529	99.8	98.4
21	2021	VW	ID4	Pro	48k	Type 2/CCS	82	3	16/6	16.3/6	11.54	4.31	91.25	89.86	703	594	99.8	98.4
22	2021	MG	Marvel R		47k	Type 2/CCS	69.9	3	16/6	15.05/5.76	10.57	4.05	90.92	84.61	507	473	99.7	98.9
23	2022	VW	ID4	GTX	53k	Type 2/CCS	82	3	16/6	15.9/6	11.01	4.22	89.80	85.99	633	493	99.8	99
24	2022	VW	Multivan		45k	Type 2/CCS	13	1	16/6	16.5/6	3.58	1.31	77.29	54.12	362	290	99.3	95.8
25	2022	Nissan	Townstar	N-Connecta	34k	Type 2/CCS	45	3	32/6	29.82/6.95	21.08	4.73	90.91	81.08	4970	−445	99.9	0
26	2022	Tesla	Model Y	Long range Dual Motor	59k	Type 2/CCS	78.1	3	16/6	16.4/6	11.32	4.27	90.34	86.39	39	-15	99.9	99.9
27	2022	Peugeot	e-208		30k	Type 2/CCS	50	3	16/6	15/6	10.27	4.11	90.83	85.61	504	460	99.8	98.9
28	2022	VW	ID3	Pro	35k	Type 2/CCS	62	3	16/6	16.3/5.2	11.3	4.18	90.95	87.43	536	480	99.7	98.6
29	2022	MG	5	Long Range	38k	Type 2/CCS	61.1	3	16/6	15.01/5.7	10.59	3.99	91.48	88.97	499	462	99.7	99
30	2022	Hyundai	Kona	Electric	43k	Type 2/CCS	67.5	3	16/6	16.5/4.76	11.16	3.16	93.08	90.59	1788	726	99.5	91
31	2022	Kia	e-Niro		42k	Type 2/CCS	67.5	3	16/6	16.2/6	11.51	4.17	91.53	90.11	722	437	99.9	98.2
32	2022	Kia	EV6	Long Range	56k	Type 2/CCS	77.4	3	16/6	15.9/6	11.3	4.23	91.87	89.37	606	472	99.6	98.7
33	2022	Renault	Megan	E-tech	47k	Type 2/CCS	65	3	16/6	16.5/6	11.14	4.09	92.8	89.57	523	471	99.8	98.8
34	2022	Nissan	Aryia		63k	Type 2/CCS	87	3	32/6	32.1/5.88	22.15	4.06	92.37	89.68	610	522	99.8	98.8
35	2022	Nissan	LEAF	e+	37k	Type 2/Chademo	62	1	32/6	29/6	6.65	1.4	89.1	76.7	306	191	99.7	98
36	2022	Polestar	2	Standard range Single Motor	47k	Type 2/CCS	69	3	16/6	16.3/5.94	11.3	4.26	–	–	443	184	99.9	99.3
37	2022	Polestar	2	Long Range Dual Motor	55k	Type 2/CCS	78	3	16/6	16.2/5.9	11.18	4.18	–	–	440	185	99.9	99.3
38	2022	Volvo	XC40	Recharge	48k	Type 2/CCS	69	3	16/6	16.14/5.88	11.1	4.02	–	–	425	174	99.9	99.5

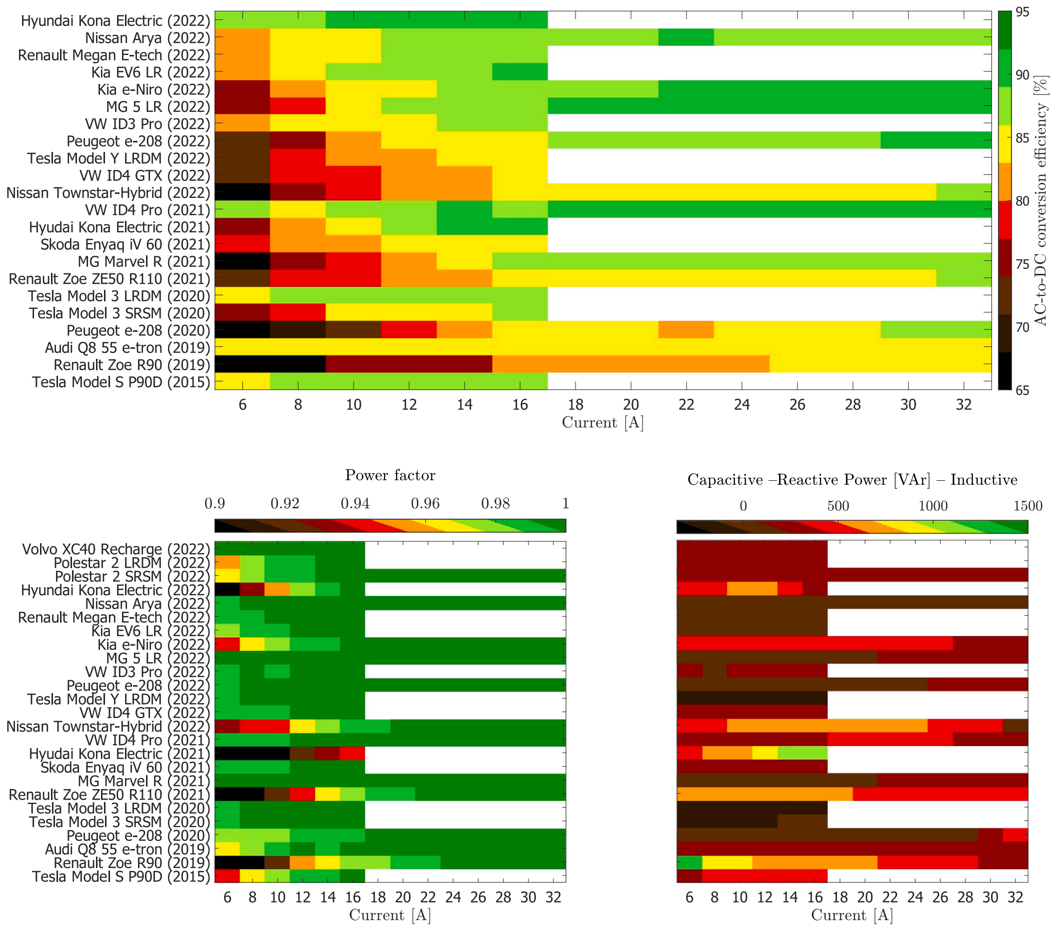


Fig. 5. Characteristics of the curtailed three-phase EV OBC (up) AC-to-DC conversion efficiency, (down-left) PF, and (down-right) reactive power consumption from 2015 to 2022.

mismatches, and some even overshoot the official max values. The data are not conclusive on whether such a pattern is dedicated to a particular brand; thus adding uncertainty to the smart charging process.

The uncertainty expands towards official active power when considering grid voltage oscillations. The official maximum active power values are 3.68 kW (16 Amps) or 7.36 kW (32 Amps) for single-phase charging and 11.04 kW (16 Amps) or 22.08 kW (32 Amps) for three-phase charging. However, such values do not match by vehicles; see Table 1. The reason for this discrepancy is the IEC 61851 standard. The standard quantifies an upper limit for the duty cycle; however, it does not quantify the quality of following such a duty cycle for the vehicle. This issue complicates smart charging control and hinders the ability of aggregators to forecast real-time demand.

Smart charging curtailment

EVs that have a three-phase OBC can charge in a single phase by curtailing two phases [49]. This curtailment is vital for places that are limited to a single-phase grid connection. The importance of curtailed charging increases for residential areas because it can be combined with single-phase photovoltaic (PV) installations. Thus, increasing the utilization and economic benefits of residential PV and the ownership of an EV.

Fig. 5 displays the curtailed efficiency of the tested models. The position of vehicles on the heat map is randomly chosen. The coloring label for AC-to-DC conversion efficiency is limited from 65%–95% to provide a clear view of the evolution of efficiency over the years and brands.

The data show that efficiency deteriorates when the three-phase OBCs are forced to charge on a single phase. Again, Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2021), and Nissan Townstar (2022) have 0% efficiency at a charging current of 6 Amps in a curtailed charging mode. Additionally, the curtailed data reconfirm that the same models from different production years experience different results.

Moreover, the ability to draw more current in a single phase is observed for some of the models. For example, Kia e-Niro in three phases can draw 16 Amps on each phase. However, when the Kia e-Niro is in curtailed charging mode, it can draw up to 32 Amps from a single phase. This capability is not common and should be verified on a vehicle-model basis.

Furthermore, Fig. 5 introduces the PF and the reactive power consumption of the curtailed OBC. PF of 1 means that all the power supplied is being used to perform useful work, while a PF of less than 1 indicates that some of the power is being wasted. Similarly to Fig. 5 the PF values deteriorate during curtailed charging. While for three-phase charging the average reactive power consumption was 800 VAr, for curtailed charging it is 400 VAr. The higher reactive power consumption agrees with vehicles that have a lower PF. Consequently, the results show that some vehicles charging on low currents do not comply with the requirements for low-voltage demand installation. Renault Zoe R90 (2019), Renault Zoe ZE50 R110 (2020), and Hyundai Kona Electric (2021,2022) have a PF lower than 0.9 for currents less than 8 Amps. In addition, the lack of capacitive behavior is the most important change in the reactive power consumption pattern during curtailed charging.

Three-phase versus curtailed charging

The possibility of curtailing three-phase charging OBCs opens up the opportunity to better optimize charging operation in parking lots, fleets, or clusters controlled by an aggregator. Such a strategy has as its objective the fulfillment of the required energy demand (in kWh) without compromising the grid capacity connection (in kW) and the allowed consumption of reactive power (in kVAr).

Grid connection capacity is generally the biggest constraint for charge-point operators. Therefore, smart charging is employed to maintain the acquired grid connection capacity from the distribution system operator (DSO). However, modulating the charging current has additional implications for OBC efficiency, as shown in Fig. 6.

The OBC efficiency results can be clustered into six patterns.

1. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and single-phase (3.68 kW) (cluster representative Skoda Enyaq iV 60). The efficiency of single-phase charging is lower than three-phase charging.
2. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and single-phase (3.68 kW) (cluster representative Hyundai Kona Electric). The efficiency of single-phase charging above 14 Amps (3.22 kW) is higher than the efficiency of three-phase charging below 8 Amps (5.52 kW).
3. Vehicle that charges with 32 Amps in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Renault Zoe ZE50 R110). The efficiency of single-phase charging greater than 16 Amps (3.68 kW) is higher than the efficiency of three-phase charging below 12 Amps (8.28 kW).
4. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and 32 Amps in single-phase (7.36 kW) (cluster representative Kia e-Niro). The efficiency of single-phase charging is lower than three-phase charging.
5. Vehicle that charges with 16 Amps in three-phase (11.04 kW) and 32 Amps in single-phase (7.36 kW) (cluster representative Peugeot e-208). The efficiency of single-phase charging is sometimes better than that of three-phase charging.
6. Vehicle that charges with 32 Amps in three-phase (22.08 kW) and single-phase (7.36 kW) (cluster representative Nissan Arya). The efficiency of single-phase charging is lower than three-phase charging.

Moreover, curtailed charging should be carefully considered if it is viable by also considering the reactive power consumption. Fig. 6(a, b and c) introduces the pattern of reactive power consumption for curtailed charging.

Similarly to three-phase charging, there are six typical curves for curtailed charging. However, two patterns behave differently, specifically Hyundai Kona and Renault Zoe. Finally, when curtailed charging is considered, the three-phase reactive power is not equal to that of three single-phase charging. Here, there are two options:

1. Lower reactive power consumption. For example, Kia EV6 Long Range (LR) consumes 471–606 VAr in three-phase charging. However, it consumes 135–186 VAr in curtailed charging. Therefore, $3 \times (135 \text{ to } 186)[\text{VAr}] < (471 \text{ to } 606)[\text{VAr}]$.
2. Higher reactive power consumption. For example, polestar 2 SRSM consumes 442–183 VAr in three-phase charging. However, it consumes 368–257 VAr in curtailed charging. Therefore, $3 \times (368 \text{ to } 257)[\text{VAr}] > (442 \text{ to } 183)[\text{VAr}]$.

The results show that decision making should be made based on a vehicle model. CPOs can benefit from curtailed charging by better utilizing the available grid capacity [kW; however, curtailed charging can reduce power quality by increasing reactive power consumption [kVAr].

So far, small- or large-scale energy simulation models do not consider OBC efficiency. The results presented in this paper highlight the importance of considering such an approach. Depending on the level of modulation required, smart charging could increase the charging energy demand from 1%–10%. Furthermore, the testing campaign showed that efficiency varies between years and vehicle models. These curves are suggested to be implemented on large-scale simulations as a lookup table; otherwise, for better dynamics, every model should be modeled accordingly to the data presented in this paper. However, it is acknowledged that such a method can be computationally heavy. Thus, a more generalized approach is proposed in Fig. 7. Based on the test results, a second-order polynomial is fitted for three-phase, curtailed, and single-phase vehicles. Such polynomials can be replicated to calculate the energy efficiency of EVs in an aggregated manner or for large-scale simulations.

Conclusions

The proposed testing methodology for commercial EV OBCs is proven successful and greatly facilitates vehicle diagnostics. This method relies on having data access at OBDII. The testing campaign highlights that open data from automakers are relevant and could be used for multiple objectives. The OBDII readings can serve independent actors to analyze the performance of OBC and can help:

1. Aggregators to better optimize their fleets and sites, along with providing grid services to grid operators.
2. Regulators to better inform and protect the consumer and require more efficient products from automakers.
3. Consumers to explore possibilities to interact with locally distributed technologies.
4. Academia to expand their research on power electronics, charging behavior, and battery degradation.

The approach to the commercialization of the OBDII data can hinder the progress of EVs and their potential for the transport and power industry. Therefore, automakers should recognize that penetration of EV is a challenge for grid operators and OBDII data can help to better operate and plan the power grid.

Furthermore, the IEC 61851 standard does not define the efficiency values allowed during the modulation of the charging current. This needs to be addressed with an approach similar to the European or California Energy Commission Efficiency for solar inverters. Consequently, regulators can require more efficient technology from automakers. Otherwise, based on the data from this testing campaign, for older models, lowering the current too much (e.g., below 10 A) could lead to areas of low efficiency, and therefore increasing charging losses. However, newer models give more freedom to take full advantage of charging modulation without incurring a significant increase in charging losses.

The global EV fleet efficiency is highly variable between models. Three-phase EVs have higher efficiency (87%–90%) than single-phase

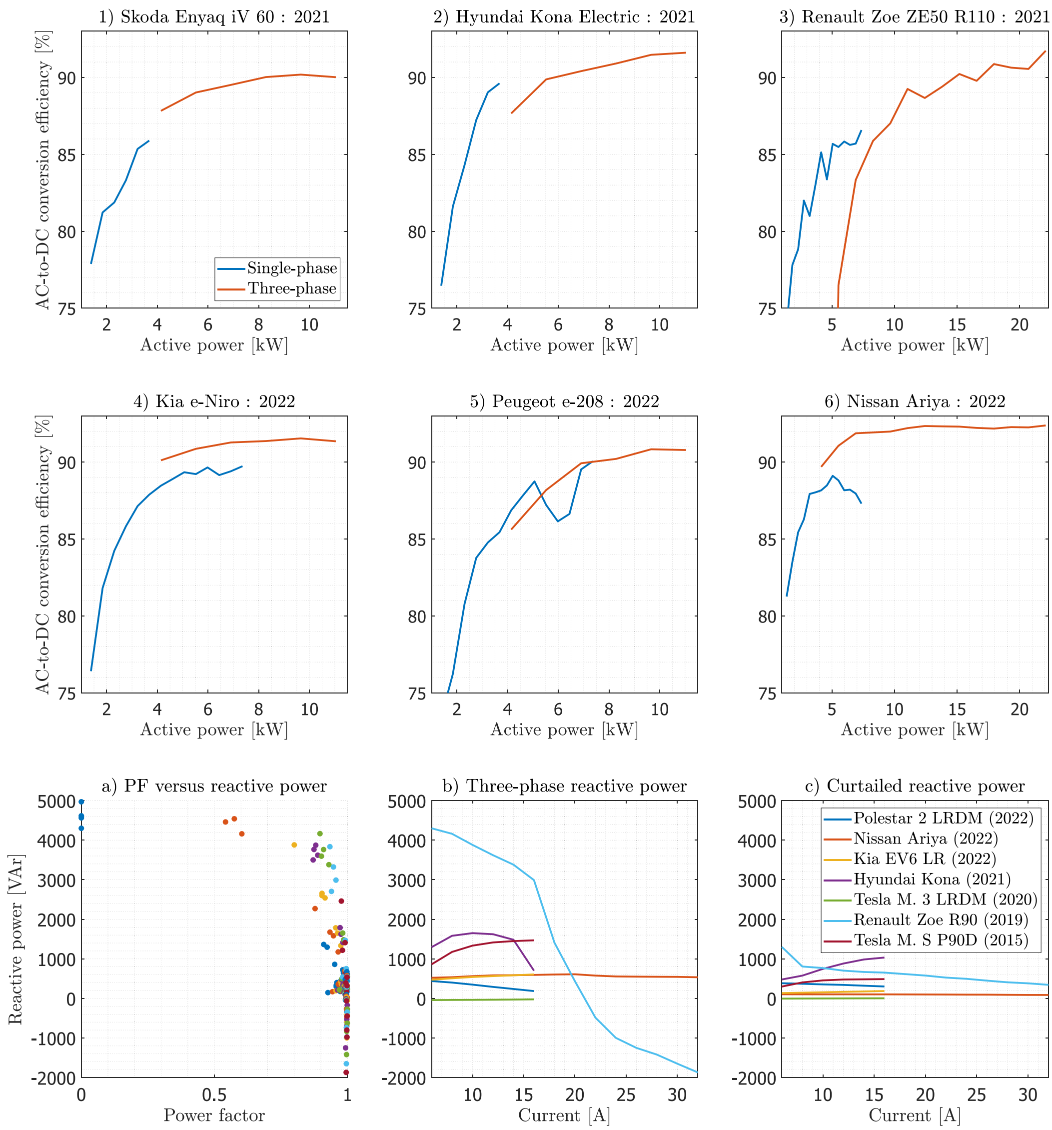


Fig. 6. Clusters of OBC efficiency comparison between a curtailed single-phase and a three-phase charger (1–6). Depending on which efficiency pattern the vehicle belongs, the charging process can be optimized by looking at such efficiency curves. The correlation between lower PF and higher reactive power consumption (a). Seven patterns of (b) three-phase reactive power consumption are similarly experienced during (c) curtailed reactive power consumption.

(78%–88%) EVs. However, curtailed three-phase EVs have an efficiency similar (78%–87%) to single-phase EVs. Overall, by 2030 the EV fleet could achieve efficiency values of 88%–95% and the OBC technology could saturate by 2035 with 90%–96% efficiency. This prediction takes into account a conservative approach from 11 years of data from 38 models. The solution to higher efficiency can come from building OBCs on a modular approach.

As shown in the data, reactive power consumption is not a strong point for many automakers. In fact, some models when charging with a current below 10 Amps violate low-voltage network code by experiencing a PF smaller than 0.9. Due to their large power size and distributed location, regulators should demand close to unity PF from EVs. In addition, to promote smart charging, the power factor correction of OBCs should be optimized for the entire charging current range, similar to Tesla models.

The IEC 61851 standard only quantifies an upper-limit charging current. As data show, this approach hampers the market participation of EV fleets in the Power Markets, because BMS decides on its own how much charging current OBC should draw.

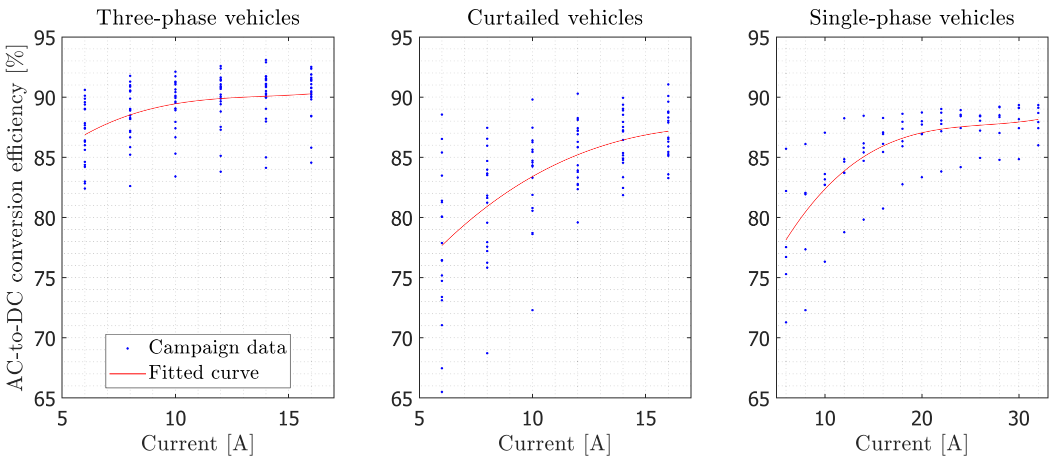


Fig. 7. Efficiency fitted curves based on the data from the testing campaign for (left) three-phase, (middle) curtailed, and (right) single-phase vehicles.

Finally, there is a high demand for better energy simulation models that include EV efficiency. Better results can be achieved by considering each vehicle's efficiency curve; however, such an approach can reduce the computing capabilities. Thus, a feasible computational solution can be found to implement the aggregated efficiency curve.

Future studies can integrate the findings of this article with measurements from full charging sessions (0%–100% state-of-charge SOC) to detect how efficient the vehicle model is during the typical charging session. Future work should focus on expanding the investigation to other automakers, with a special focus on 800 V architecture models, and analyzing the harmonics of OBCs. Additionally, the efficiency values can be combined with the charging curve to determine the efficiency of the charging session.

CRediT authorship contribution statement

Kristian Sevdari: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. **Lisa Calearo:** Methodology, Investigation, Writing – review & editing, Formal analysis. **Bjørn Harald Bakken:** Methodology, Writing – review & editing, Supervision, Institutional support for the research. **Peter Bach Andersen:** Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition. **Mattia Marinelli:** Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The work in this article is supported by the Danish research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092). The authors thank Magnus Fich Rabjerg, Daniel Arndtzen, Oliver Gehrke, Rasmus Meier Knudsen, Valdemar Cornelio Foss, and Irisa Sevdari for helping on such a testing campaign. Moreover, we are grateful to each participant in the testing campaign, and the fruitful collaboration with Lene Mejdal Iversen (from KIA and MG), Steffen Høj (from Polestar), and Steffen Martiena (from Nissan).

Appendix A: Testing tools

Figs. A.1(a) provides a screenshot of the smartphone applications that were used during the testing campaign. As mentioned in the methodology, the data shown in the applications is proven correct and very useful for EVs investigation. Furthermore, Fig. A.1(b) displays the Type 2-to-Type 1 plug converter that is used for older EV models (2011–2012) that rely on the Type 1 plug.

Moreover, Table A.1 provides a summary of the tools needed to investigate each automaker.

Appendix B: Automakers

Table B.2 summarizes the electrical results and provides a bird's-eye view of each brand.

One has to note that some brands are represented only by one model and others from multiple models. Consequently, having different models per brand is highly beneficial; however, when considering the complete lack of data in such an area, it is crucial to highlight the behaviors observed in the testing campaign. The charging current on each phase is slightly unbalanced for almost all three-phase vehicles. The size of the unbalance differs in the models. Here, it should be mentioned that there are cases in which the difference is smaller than the measurement error (class 0.1). Thus, measurements below 0.1 A are within the DEIF measurement error. Table B.2 summarizes the possible phase unbalanced, scale of oscillations and additional comments on the specific vehicle model behavior. The values are averaged over the test procedure. Fig. B.2 displays the efficiency and reactive power consumption of the tested EVs when compared to their price. The data is not conclusive if a more expensive EV has higher efficiency and lower reactive power. Finally, every efficiency curve from the test campaign is displayed in Fig. B.3.

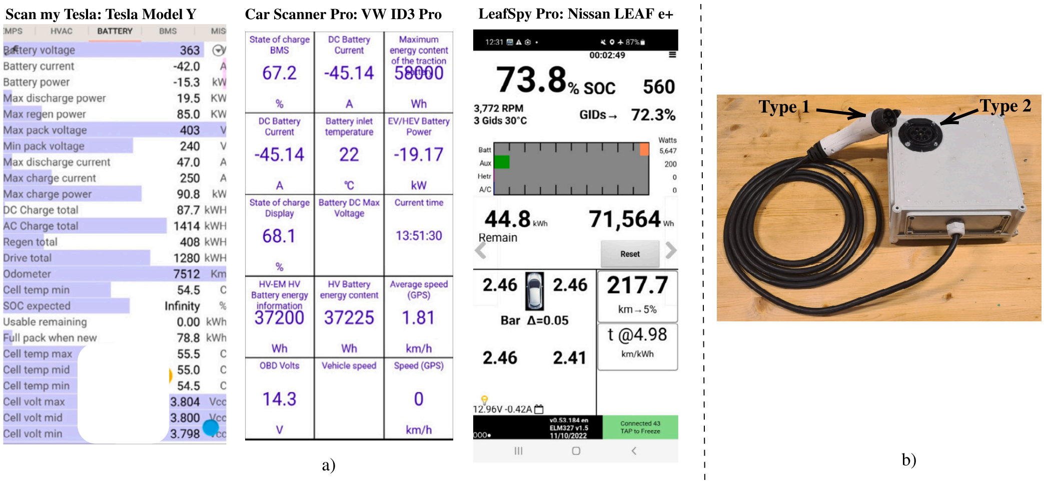


Fig. A.1. (a) Smartphone application to read the data from the EV OBDII port. (b) Type 2-to-Type 1 plug converter built at DTU- EVLab.

Table A.1
Tools for receiving the data from the tested electric vehicle brands. "+" means that OBDII data are available to read with a dongle.

Brand	OBDII reader	App	Plug	DC side data	
Audi	+ via dongle	Car Scanner Pro	Type 2	SoC Battery energy content	Charging power Charging losses
BMW	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Hyundai	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Jaguar	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Kia	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
MG	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Nissan	+ via dongle	LeafSpy Pro	Type 1and 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Peugeot	+ via dongle	Car Scanner Pro	Type 1and 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Polestar	encrypted		Type 2		
Renault	+ via dongle	Car Scanner Pro CanZe Plus	Type 2	SoC and SoH Battery energy content	Charging power
Skoda	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Tesla	+ via adapterand dongle	scan my tesla	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage
Volvo	encrypted		Type 2		
Volkswagen	+ via dongle	Car Scanner Pro	Type 2	SoC and SoH Battery energy content	Charging power DC current DC voltage

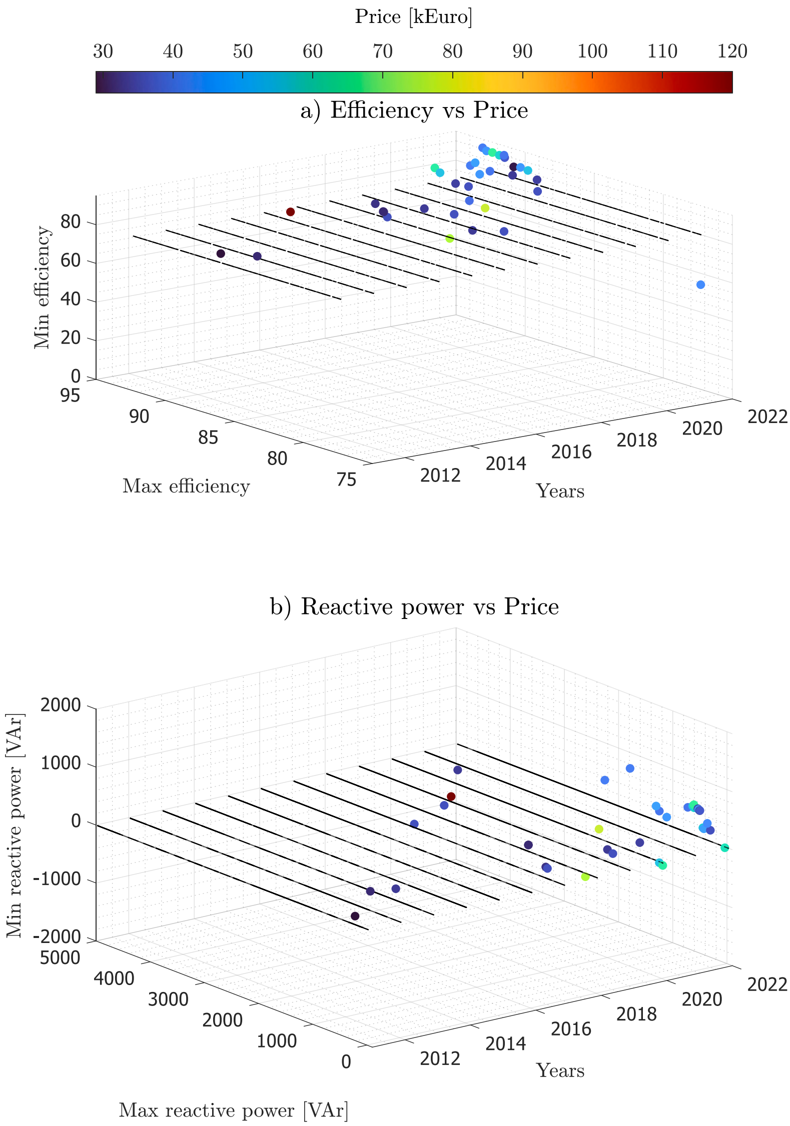


Fig. B.2. a, Correlation between years, maximum efficiency, minimum efficiency, and prices. The horizontal plane is designed at min efficiency equal to 80%. b, Correlation between years, maximum/minimum reactive power, and prices. The horizontal plane is designed at min reactive power to 0 VAr.

Table B.2
Summary of electrical characteristics for charging behavior. Oscillations on the grid are classified as i) not visible (<0.1 A); ii) small (0.1–0.3 A) and iii) moderate (0.3–0.5 A).

Brand	Phase unbalance grid side	Oscillations grid side	Comments
Audi	20 W or 0.08 A	Small	
BMW			- Reactive power in one of phases is capacitive and two others are inductive.
Hyundai	40 W or 0.16 A	Small	-It has difficulties in adequately following the control pilot (CP) at high SOC.
Jaguar	–	Small	-Reactive power consumption changes the state from inductive (below 28 A) to capacitive (28 A and above).
Kia	EV6: 20 W or 0.08 A e-Niro: 60 W or 0.24 A	EV6: not visible e-Niro: moderate	-Kia EV6 has reactive power disbalance between phases (50 VAr).
MG	MG 5: 70 W or 0.3 A Marvel R: 60 W or 0.24 A ZS EV: -	MG 5: small Marvel R: small ZS EV: small	-MG 5 has difficulties in adequately following the CP. (1 A of difference) - MG Marvel R has difficulties in adequately following the CP (1 A of difference). -MG ZS EV experience higher reactive power on higher charging currents.
Nissan	LEAF: - Arya: 20 W or 0.08 A Townstar: 10 W or 0.04A	LEAF: small Arya: not visible Townstar: not visible	-Nissan Arya has a higher reactive power disbalance between phases on higher charging currents and almost linearly reduces towards lower charging currents (80 to 5 VAr). -Nissan Townstar, as the data suggest, has a Chameleon charger. Reactive power consumption changes state from inductive (below 18 A) to capacitive (18 A and above).
Peugeot	e-208: 10 W or 0.04A iOn: -	e-208: not visible iOn: small	-Reactive power for e-208 increases in small amounts as the charging current increases. It has difficulties in adequately following the CP (1 A of difference).
Polestar	30 W or 0.12 A	moderate +	
Renault	Megan E-tech: Zoe: 10 W or 0.04A	Megan E-tech: not visible Zoe: not visible	-Reactive power for Megan E-tech increases in small amounts (10 VAr) as charging currents increase. - Renault Zoe employs a Chameleon charger. Reactive power consumption changes the state from inductive (below 20 A) and capacitive (20 A and above).
Skoda	20 W or 0.08 A	small	
Tesla	Model 3: 40 W or 0.16 A Model Y: 20 W or 0.08 A Model S: 40 W or 0.16 A	Model 3: not visible Model Y: small Model S: small	- Model S P90D has difficulties in adequately following the CP (1 A of difference).
Volvo	30 W or 0.12 A	moderate +	-The data shows that Volvo XC40 Recharge shares same dynamics with Polestar 2 LRDM.
VW	ID4: 30 W or 0.12 A ID3: 20 W or 0.08 A e-golf: 40 W or 0.16 A	ID4: small ID3: not visible e-golf: small	

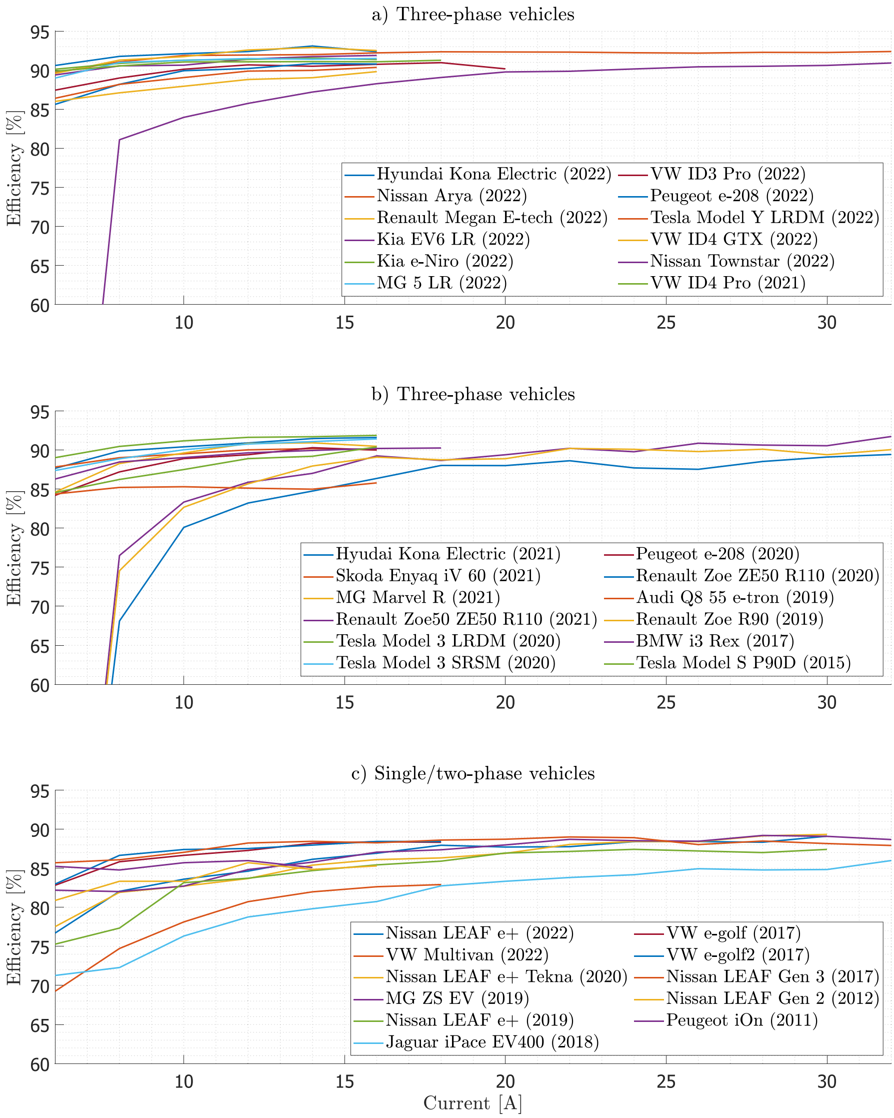


Fig. B.3. Electric vehicle onboard charger efficiency patterns from the testing campaign.

References

[1] Bauer C, Hofer J, Althaus HJ, Del Duce A, Simons A. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Appl Energy 2015;157:871–83.

[2] Degefa MZ, Sperstad IB, Sæle H. Comprehensive classifications and characterizations of power system flexibility resources. Electr Power Syst Res 2021;194(January):107022.

[3] Chen Y, Huang M, Tao Y. Density-based clustering multiple linear regression model of energy consumption for electric vehicles. Sustain Energy Technol Assess 2022;53(PD):102614.

[4] Navon A, Nitskansky R, Lipman E, Belikov J, Gal N, Orda A, et al. Energy storage for mitigating grid congestion caused by electric vehicles: A techno-economic analysis using a computationally efficient graph-based methodology. J Energy Storage 2023;58(December 2022):106324.

[5] Calearo L, Thingvad A, Suzuki K, Marinelli M. Grid loading due to EV charging profiles based on pseudo-real driving pattern and user behavior. IEEE Trans Transp Electrification 2019;5(3):683–94.

[6] Yang X, Zhang Y. A comprehensive review on electric vehicles integrated in virtual power plants. Sustain Energy Technol Assess 2021;48(October):101678.

[7] Anwar MB, Muratori M, Jadun P, Hale E, Bush B, Denholm P, et al. Assessing the value of electric vehicle managed charging: a review of methodologies and results. Energy Environ Sci 2022;15(2):466–98.

[8] Solanke TU, Ramachandaramurthy VK, Yong JY, Pasupuleti J, Kasinathan P, Rajagopalan A. A review of strategic charging–discharging control of grid-connected electric vehicles. J Energy Storage 2020;28(September 2019):101193.

[9] Resch M, Buhler J, Schachler B, Sumper A. Techno-Economic assessment of flexibility options versus grid expansion in distribution grids. IEEE Trans Power Syst 2021;36(5):3830–9.

[10] Alsharif A, Tan CW, Ayop R, Dobi A, Lau KY. A comprehensive review of energy management strategy in Vehicle-to-Grid technology integrated with renewable energy sources. Sustain Energy Technol Assess 2021;47(June):101439.

[11] Englberger S, Abo Gamra K, Tepe B, Schreiber M, Jossen A, Hesse H. Electric vehicle multi-use: Optimizing multiple value streams using mobile storage systems in a vehicle-to-grid context. Appl Energy 2021;304(September):117862.
[12] Richardson P, Flynn D, Keane A. Local versus centralized charging strategies for electric vehicles in low voltage distribution systems. IEEE Trans Smart Grid 2012;3(2):1020–8.
[13] Calearo L, Marinelli M. Profitability of frequency regulation by electric vehicles in Denmark and Japan considering battery degradation costs. World Electric Veh J 2020;11(3):48.
[14] Thingvad A, Calearo L, Andersen PB, Marinelli M. Empirical capacity measurements of electric vehicles subject to battery degradation from V2G services. IEEE Trans Veh Technol 2021;70(8):7547–57.
[15] Sevdari K, Calearo L, Andersen PB, Marinelli M. Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives. Renew Sustain Energy Rev 2022;167(December 2021):112666.
[16] Metere R, Neaimeh M, Morisset C, Maple C, Bellekens X, Czekster RM. Securing the electric vehicle charging infrastructure. 2021, arXiv preprint arXiv:2105.02905.
[17] Afentoulis KD, Bampos ZN, Vagropoulos SI, Keranidis SD, Biskas PN. Smart charging business model framework for electric vehicle aggregators. Appl Energy 2022;328(September):120179.
[18] Villar J, Bessa R, Matos M. Flexibility products and markets: Literature review. Electr Power Syst Res 2018;154:329–40.
[19] Neaimeh M, Andersen PB. Mind the gap- open communication protocols for vehicle grid integration. Energy Informatics 2020;3(1):1–17.
[20] Gonzalez Venegas F, Petit M, Perez Y. Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services. Renew Sustain Energy Rev 2021;145(March):111060.
[21] Calearo L, Ziras C, Sevdari K, Marinelli M. Comparison of smart charging and battery energy storage system for a PV prosumer with an EV. In: IEEE PES ISGT Europe. 2021.
[22] Unterluggauer T, Hipolito F, Klyapovskiy S, Andersen PB. Impact of electric vehicle charging synchronization on the urban medium voltage power distribution network of Frederiksberg. World Electric Veh J 2022;13(10):1–18.
[23] Ziras C, Heinrich C, Pertl M, Bindner HW. Experimental flexibility identification of aggregated residential thermal loads using behind-the-meter data. Appl Energy 2019;242(March):1407–21.
[24] Lanz L, Noll B, Schmidt TS, Steffen B. Comparing the levelized cost of electric vehicle charging options in europe. Nature Commun 2022;13(1).
[25] Khaligh A, Dantonio M. Global trends in high-power on-board chargers for electric vehicles. IEEE Trans Veh Technol 2019;68(4):3306–24.
[26] Mutarraf MU, Guan Y, Xu L, Su CL, Vasquez JC, Guerrero JM. Electric cars, ships, and their charging infrastructure – A comprehensive review. Sustain Energy Technol Assess 2022;52(PB):102177.
[27] Rivera S, Kouro S, Vazquez S, Goetz SM, Lizana R, Romero-Cadaval E. Electric vehicle charging infrastructure: From grid to battery. IEEE Ind Electron Mag 2021;15(2):37–51.
[28] Dai Z, Zhang B. Electric vehicles as a sustainable energy technology: Observations from travel survey data and evaluation of adoption with machine learning method. Sustain Energy Technol Assess 2023;57(January):103267.
[29] USDepartment of Energy. Electrical and electronics technical team roadmap. U.S. DRIVE Partnership 2017;(October):9.
[30] Schmenger J, Endres S, Zeltner S, März M. A 22 kw on-board charger for automotive applications based on a modular design. In: 2014 IEEE conference on energy conversion. 2014, p. 1–6.
[31] Cesiel D, Zhu C. A closer look at the on-board charger: The development of the second-generation module for the Chevrolet volt. IEEE Electrif Mag 2017;5(1):36–42.
[32] Lebrouhi BE, Khattari Y, Lamrani B, Maaroufi M, Zeraouli Y, Kousksou T. Key challenges for a large-scale development of battery electric vehicles: A comprehensive review. J Energy Storage 2021;44(PB):103273.
[33] Hasan MK, Mahmud M, Ahasan Habib AK, Motakabber SM, Islam S. Review of electric vehicle energy storage and management system: Standards, issues, and challenges. J Energy Storage 2021;41(July):102940.
[34] Hussain MT, Sulaiman DNB, Hussain MS, Jabir M. Optimal management strategies to solve issues of grid having electric vehicles (EV): A review. J Energy Storage 2021;33(October 2020):102114.
[35] García A, Monsalve-Serrano J, Martinez-Boggio S, Tripathi S. Techno-economic assessment of vehicle electrification in the six largest global automotive markets. Energy Convers Manage 2022;270(September):116273.
[36] Mangipinto A, Lombardi F, Sanvito FD, Pavičević M, Quoilin S, Colombo E. Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries. Appl Energy 2022;312(February):118676.
[37] European Commission. Ecodesign impact accounting annual report 2020 : overview and status report. Tech. rep., Directorate-General for Energ; 2020.
[38] European Commission. Communication from the commission: Ecodesign and Energy Labelling Working Plan 2022–2024. Tech. rep., 2022.
[39] Faure C, Guetlein MC, Schleich J. Effects of rescaling the EU energy label on household preferences for top-rated appliances. Energy Policy 2021;156(June):112439.
[40] International Energy Agency. Electric vehicles: Total cost of ownership tool. 2022.
[41] Mouli GRC, Venugopal P, Bauer P. Future of electric vehicle charging. In: 19th International symposium on power electronics, 017-December. 2017, p. 1–7.
[42] International Electrotechnical Commission. IEC 61851. 2017.
[43] Calearo L, Ziras C, Thingvad A, Marinelli M. Agnostic battery management system capacity estimation for electric vehicles. Energies 2022;15(24):9656.
[44] Marinelli M, Calearo L, Engelhardt J, Rohde G. Electrical thermal and degradation measurements of the LEAF e-plus 62-kwh battery pack. In: 2022 International conference on renewable energies and smart technologies, vol. 1. 2022, p. 1–5.
[45] Calearo L, Thingvad A, Ziras C, Marinelli M. A methodology to model and validate electro-thermal-aging dynamics of electric vehicle battery packs. J Energy Storage 2022;55(PB):105538.
[46] Car Scanner ELM OBD2. Car Scanner Elm OBD2.
[47] Leaf Spy Pro. Leaf Spy Pro.
[48] Scan my tesla. Scan my tesla.
[49] Sevdari K, Striani S, Andersen PB, Marinelli M. Power modulation and phase switching testing of smart charger and electric vehicle pairs. In: 2022 57th International universities power engineering conference. IEEE; 2022, p. 1–6.
[50] Abdelrahman AS, Erdem Z, Attia Y, Youssef MZ. Wide bandgap devices in electric vehicle converters: A performance survey. Can J Electr Comput Eng 2018;41(1):45–54.
[51] Srivastava M, Tomar PS, Verma AK. Emphasis on switch selection and its switching loss comparison for on-board electric vehicle charger. IET Power Electron 2019;12(6):1385–92.
[52] DEIF A/S. DEIF multimeter documentation.
[53] Green Power Denmark. Guide for grid connection of demand installations to the low-voltage grid, no. November. Tech. rep., 2022, p. 1–42.
[54] Rampinelli G, Krenzinger A, Romero FC. Mathematical models for efficiency of inverters used in grid connected photovoltaic systems. Renew Sustain Energy Rev 2014;34:578–87.
[55] EV Database. Electric Vehicle Database.

PAPER [P5]

Power Modulation and Phase Switching Testing of Smart Charger and Electric Vehicle Pairs

Authors:

Kristian Sevdari, Simone Striani, Peter Bach Andersen, Mattia Marinelli

Published in:

Proceedings of the 2022 57th International Universities Power Engineering Conference (UPEC)

DOI:

10.1109/UPEC55022.2022.9917660.

Power Modulation and Phase Switching Testing of Smart Charger and Electric Vehicle Pairs

Kristian Sevdari, Simone Striani, Peter Bach Andersen, Mattia Marinelli
Department of Wind and Energy Systems
Technical University of Denmark (DTU)
Roskilde, Denmark
{krisse; sistri; petb; matm}@dtu.dk

2022 57th International Universities Power Engineering Conference (UPEC) | 978-1-6654-5505-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/UPEC55022.2022.9917660

***Abstract*—De-coupling transport sector from the use of petroleum is giving way to the rise of electric mobility. As compromising the user's comfort is not an option managing the power system becomes a tall challenge, especially during peak hours. Thus, having a smart connection to the power system, such as an electric vehicle (EV) smart charger, is considered part of the solution. This paper focuses on assessing the capabilities of smart chargers in the context of helping the electrical network without compromising the user's comfort. By using a Tesla Model S P85, Renault Zoe, and Nissan LEAF, the paper first evaluates differently controlled (centralized and distributed) smart chargers against the IEC 61851 standard. Second, it tests smart features such as peak-shaving, valley-filling, and phase balancing. Being representatives of the state-of-the-art, both chargers exceed standard requirements and offer new grid service possibilities. However, the bottleneck for providing faster grid services remains the EV on-board charger. The results from this article can help to better simulate the dynamic charging behaviors of EVs.**

***Index Terms*—smart chargers, charging modulation, phase switching, electric vehicles**

I. Introduction

As the EV technology matures and becomes a more commercially viable option for the masses, it is expected to gain high market share. This is reflected in the relatively large amount of research being done on vehicle-to-grid integration and user behavior [1]. Furthermore, in European countries, EVs, being batteries on wheels, are on average parked 97% of the time with an average driving between 40-80 km/day [2]. Here, the fulfillment of charging needs, if left uncontrolled may harm the distribution grid [3]. The authors of [4] describe potential harmful impacts on the distribution grid as i) increase in peak demand and power losses; ii) voltage instability and power quality issues; iii) grid components overloading. Thus, EVs can become a large flexibility asset for the power system by coordinating their flexible demand according to the system needs (also called demand-side management) [5]. To be able to take advantage of this flexibility from EVs, there is a need for large coordination between flexibility resources, flexibility markets, aggregators, energy communities, and system operators at the distribution and transmission levels [6]. In addition, a hidden layer is the charging behavior of end-users, which is still quite early to have a sufficient understanding and makes flexibility allocation prone to overestimation [7]. Nonetheless, authors of [8] quantify the driving energy demand to be covered 78% from households and the rest outside the private household environment. Furthermore, to determine the residential flexibility margins, authors of [9] look at driving requirements, parked period, battery capacity, and charging speed. By doing so, they propose a certain charging coincidence factor (CF) that reflects the frequency of charging on the residential ground. More specifically, the larger the number of EVs, smaller becomes the CF and it is more dependent on charging power rather than the EVs battery capacity. To complement this, the authors of [10] investigated the non-systematic plug-in behavior. They concluded that a larger battery size EVs offers less flexibility in terms of power (kW) and storage (kWh) due to a lower plug-in frequency and higher energy needs per charging session. Therefore, to tackle these challenges, a smart infrastructure, such as smart chargers, promises to unravel the complexity for the end-user. Especially beneficial is the coupling of residential flexibility for the safe operation of the grid with economic and environmental benefits for the EV owner [11]. Previously, smart charger was defined as *"a device offering communication, protection and at minimum scheduling or at maximum modulation and phase curtailment for the charging process"* [12]. Therefore, by focusing on smart chargers, the main contributions of this paper are as follows:

1) Test the capabilities of representative smart chargers (centralized and distributed architecture) to offer grid services.
2) Assess the performance (accuracy, precision and time delays) of the smart chargers and three EVs against the requirements of IEC 61851 standard [13].

The remainder of this article is structured as follows. Section II describes the control architecture and methodology behind choosing smart chargers, while Section III introduces case studies and Section IV provides the results of the tested chargers. Finally, Section V concludes the article.

II. Control architecture

A. Smart chargers state-of-the-art

The technological aspect of smart chargers, especially the control method is crucial in scaling up the charging infrastructure. The authors of [14] explain three control possibilities: i) centralized; ii) decentralized; and iii) distributed. Due to the implementation simplicity, the early stage of smart chargers belongs to the centralized control approach [12]. However, recent initiatives follow the distributed control approach introduced in [15], [16]. The rationale behind exploiting distributed control is the increased robustness to malfunctions on a large-scale deployment and the reduction of required communication together with the communication delays [17]. For both control approaches, the goal is to follow a given power setpoint by modulating or scheduling the charging process. Here, Fig.1 explains the difference between the control approaches. The intelligence in the centralized approach resides in the cloud aggregator, while on the distributed case, the intelligence resides in the virtual aggregator (VA), and the cloud aggregator serves to coordinate across areas. On the distributed case, the cloud aggregator gathers grid or market signals to better optimize the controlling actions of the local virtual aggregator. Furthermore, these smart charger control capabilities, namely scheduling or modulating the charging process, should be evaluated in relation to what is beneficial to the grid. This paper does not intend to be exhaustive on the grid service front but rather evaluates some important well-researched features such as peak-shaving, valley-filling, and phase-balancing actions. Based on previous work [12], [18], we take as state-of-the-art representatives for the centralized control approach the Zaptec charger, while the charger developed in the ACDC project for the distributed control approach from [15].

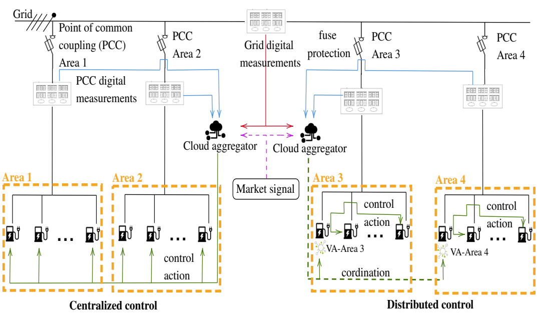


Fig. 1: Control approaches on current EVs chargers technology. VA accounts for the virtual aggregator.

B. Smart chargers assessment

Before testing and comparing the different control architectures on a complex environment, it is important to test and compare chargers directly through their communication ports. However, such testing has its limitations because smart chargers are part of the EV on-board charger. Therefore, their main control duty is to provide a pulse-width modulation (PWM) signal, which corresponds to the maximum allowed charging current, to the vehicle on-board charger. In addition, the PWM precision is defined by the IEC 61851 standard through the allowed oscillator resolution [13]. The oscillator frequency should be 1 kHz $\pm$ 0.5%, pulse width should be $\pm$ 25 μsec , and the duty cycle tolerance is $\pm$1% (or 0.6 Amps). Due to technical improvements, the tested charger manufacturers offer a much better modulation resolution than 0.6 Amps, thus, PWM timing is the only feature to be tested [19], [20]. The IEC 61851 standard demands for the smart charger a maximum of 10 seconds for the change of the pulse-width in response to external signals (t_external in the standard).

Furthermore, the IEC 61851 standard requires the EV on-board charger to respond within five seconds to a PWM change (t_ichange in the standard) (denoted as time delay in Fig.2). Additionally, having the possibility to test different EVs, Fig.2 illustrates the evaluation process for the vehicle on-board charger. The vehicle on-board charger is responsible for the vehicle charging dynamics. To evaluate such dynamics, we use the following key performance indicators (KPIs): i) the accuracy between receiving the PWM signal and the charging current, ii) the time delay between receiving a PWM signal and responding to it (the maximum allowed time is five seconds) and iii) the precision of the charging current (if it deteriorates due to change in state-of-charge (SOC)). In summary, the time delay between the two chargers, the verification of charging modulation, and three-to-one phase switching can be tested.

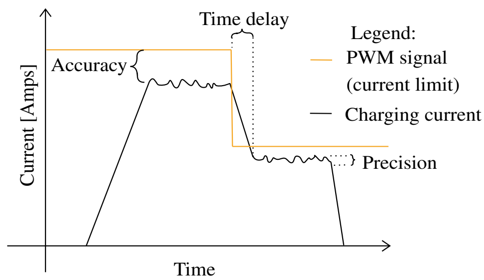


Fig. 2: Illustration of the KPIs, adapted from [21].

III. Case Study

This paper presents two case studies. The first one is a centralized architecture, while the second one is a decentralized architecture. Moreover, Fig.3 describes the laboratory setup for experiments presented in section IV. Two Zaptec chargers are connected to a lab cell (or the external grid) via a three-phase 63 Amps breaker. The size of the breaker quantifies the maximum current allowed for point of common coupling (PCC). Zaptec chargers have a certified meter inside the unit that is used to send data back to the Zaptec cloud. Furthermore, Zaptec chargers use the cloud to coordinate between them and follow a certain power threshold. In addition to that, the test setup has a DEIF multimeter connected to the University (DTU) cloud, which offers high-resolution measurements. The operator, who is conducting the experiments can utilize the web interface from the Zaptec cloud to send commands to the chargers and record the data through deif meters with a higher resolution. The difference for the ACDC charger is that it uses the DEIF multimeter connected to the DTU cloud and the PCC capacity is limited maximum 32 Amps or 22.1 kW. In both cases,the PCC capacity is intended to change, by controlling the PWM signal of the smart chargers. In doing so, we emulate the load-curtailment behavior performed by the Zaptec/ACDC charger.

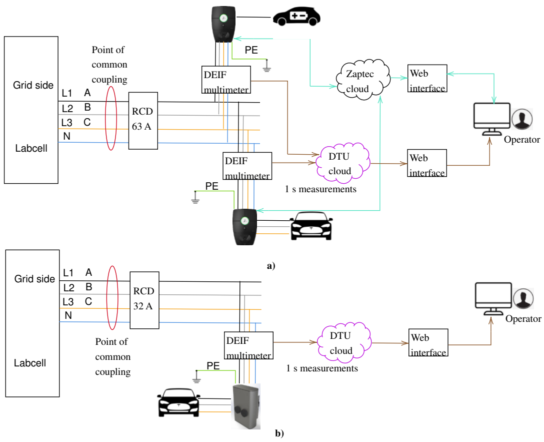


Fig. 3: Test setup for the Zaptec smart chargers (centralized) (a) and the ACDC charger (distributed) (b) in the syslab facility [22].

Lastly, Fig.4 displays the Syslab facilities where smart chargers are tested. It is important to highlight that according to the IEC 61851 standard [13] smart chargers are responsible to deliver a PWM signal (corresponding to the duty cycle) to the EV on-board charger. The quality of the PWM signal is determined by the chosen oscillator from the charger manufacturer. Such control action through the PWM signal is the end result of smart charging strategies that can include single or stacking services, for example frequency control, voltage regulation, or congestion management [23], [24].

Fig. 4: Syslab facilities [22].

IV. Results

This section presents the results from the testing of smart chargers and vehicle on-board chargers. Before elaborating on the testing procedure, it is important to highlight that both ACDC and Zaptec chargers can modulate below 0.6 Amps. The former (ACDC) can modulate in 0.06 Amps and the latter in 0.1 Amps. The first case is starting and allowing the vehicles to charger full power (Fig.5). The second case is modulating the allowed consumption of the chargers or virtually adjusting the PCC capacity. This attempts to emulate a peak-shaving or valley-filling action. Fig.6 displays the charging modulation at 5-minute intervals for Zaptec chargers.

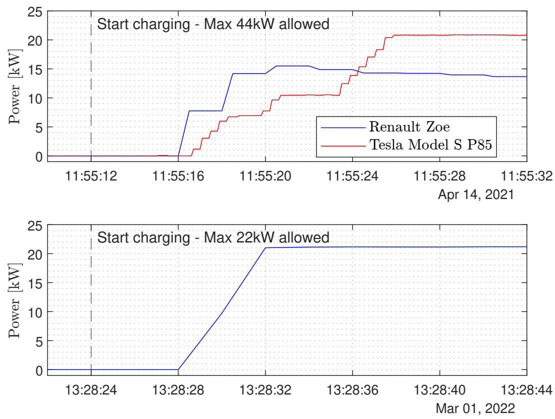


Fig. 5: (top plot) Controlling two Zaptec chargers to allow for 44 kW charging power. (lower plot) Controlling ACDC charger to allow 22 kW charging power.

The physical electrical connection allows for 44 kW; however, at time 12:29:10 it is artificially reduced (39% power reduction) to 27 kW emulating a peak-shaving action. This big step reduction was chosen to evaluate the performance of the smart charger and the on-board charger dynamics. The Zaptec cloud assesses which charger should reduce the charging power, and the one corresponding to the Tesla reduces most of the charging power. This occurs because the Zaptec chargers are by default designed to be on equal priority regarding power distribution between them. The PWM signal dictates how much power is available for each vehicle (maximum limit). Following the IEC 61851 standard (hereafter referred to as the standard) [13], EVs on-board charger should recognize the PWM signal and decide to charge according to their battery needs. One interesting aspect is the charging initial dynamics. Because the standard does not define a time for the vehicle to start drawing current, different EV manufactures have different dynamics. Furthermore, Fig.7 presents the same case, albeit for the ACDC charger. The same vehicle (Renault Zoe) is used to modulate the charging power. However, in this case, Zoe has a lower SOC (54%). The vehicle receives the PWM signal from the ACDC charger and in this case, Fig.7, Renault Zoe can better follow the PWM signal.

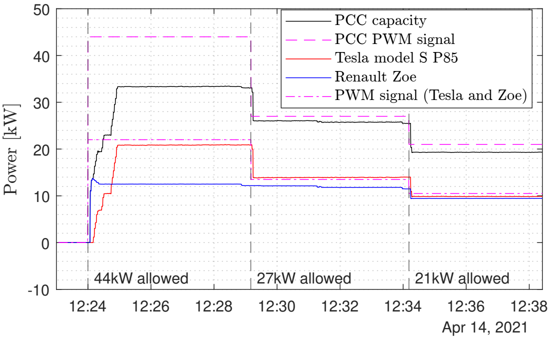


Fig. 6: Charging power modulation with Zaptec chargers.

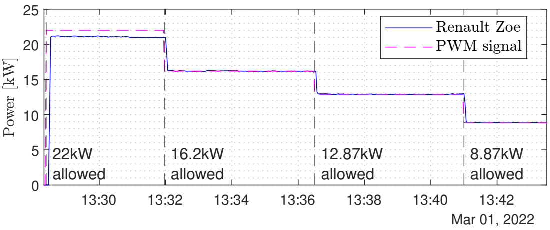


Fig. 7: Charging power modulation with ACDC charger.

Figure 8 compares the same conditions for Renault Zoe (SOC 54%) to different chargers. In such graphic PWM signal and charging power dynamics look the same. The reason we cannot identify any differences is the lack of measurement resolution (below one second). Previous research has ensured communication delays with respect to 3/4G or Ethernet communication [19], [20].

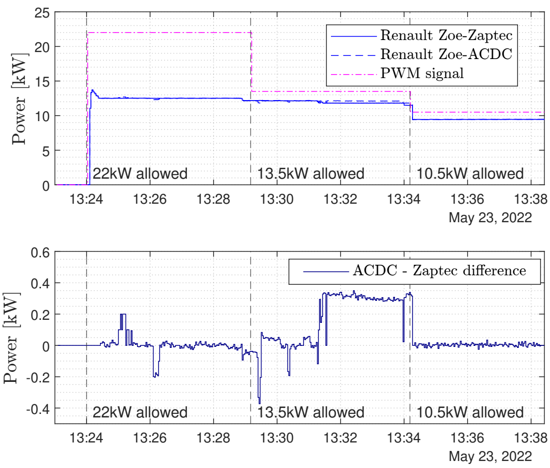


Fig. 8: (top) Same Renault Zoe, charging modulation with a Zaptec and ACDC charger.(bottom) The active power difference between charging power for ACDC and Zaptec shown on top.

The authors of [19], [20] measured such cloud communication delays using an oscilloscope and pinging the Internet service for 24 hours. If the measuring device had been in the 100-200 ms range, we would have experienced, on average, a 300-400 ms shift in time for the PWM signal and the charging dynamics. The shift in time means that the ACDC charger is faster than the Zaptec one, due to lack of cloud communication delay.

In addition to testing three-phase vehicles, Fig.9 presents testing of a single-phase charging EV with the ACDC charger.

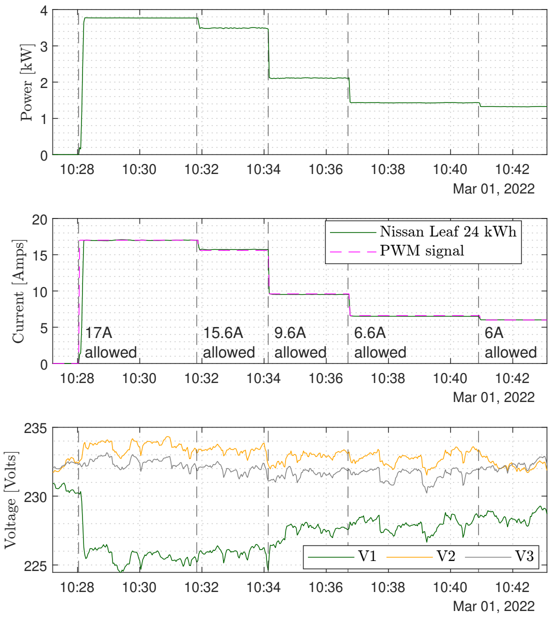


Fig. 9: (Top) Modulation of the charging power with the ACDC charger. (Middle) Current modulation with the ACDC charger. (Bottom) Voltage behavior during charging current modulation.

Here, a Nissan LEAF 24 kWh is used, which can be charged to a maximum of 3.68 kW (16 Amps). The bottom plot of Fig.9 displays the voltage behavior during the modulation of the charging current. Nissan LEAF is charging in the first phase, which corresponds to voltage V1. As expected, once the EV is charging in full power (time 10:28-10:32), the voltage reduces, and while the charging power decreases (time 10:32-10:42), the voltage increases.

Fig.10 and Fig.11 display a new feature offered by recent smart-chargers, which is the ability to switch the charging of a three-phase EV from a three-phase to one-phase. In addition, the three-to-one phase switching can be manually or automatically decided by the operator. Such capability is successfully demonstrated by both chargers. Both, Tesla and Zoe, are initially charging with 32 Amps on three-phase. After 15 seconds, the switch phase command is initiated. During the transition from three-phase to one-phase charging (Figs.10 and 11), EVs do not consume power from the grid and are not disconnected from the charging process. The three-to-one phase switching similarly initiates a single-phase charging with 32 Amps. However, the transition period is different for the tested EVs.

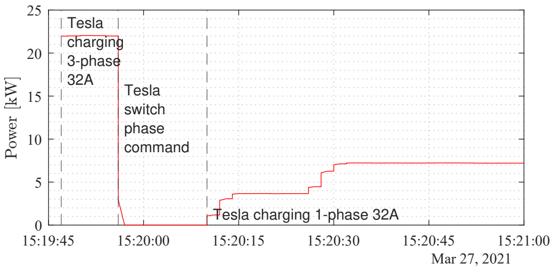


Fig. 10: Switch phase command from three-phase to one-phase charging on a Tesla Model S P85 with Zaptec charger.

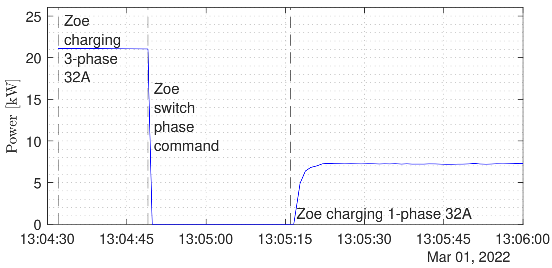


Fig. 11: Switch phase command from three-phase to one-phase charging on a Renault Zoe (41 kWh) with ACDC charger.

In this regard, Fig. 12 displays the time difference of the phase-changing action. Although both EVs react quite similarly to power reduction, there is a significant difference when one-phase charging re-starts. Another important result to mention is that the transition to one-phase charging can only be achieved through the first phase of the EV on-board charger. The vehicle enters an error state if an attempt to charge is made in a single phase through the second or third phase of the vehicle's on-board charger, as presented in Fig.13. The on-board charger can only perform single-phase charging for a three-phase vehicle through the first phase.

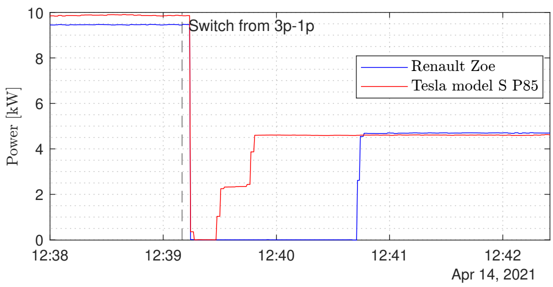


Fig. 12: Changing charging automatically from three-phase to one-phase with Zaptec chargers.

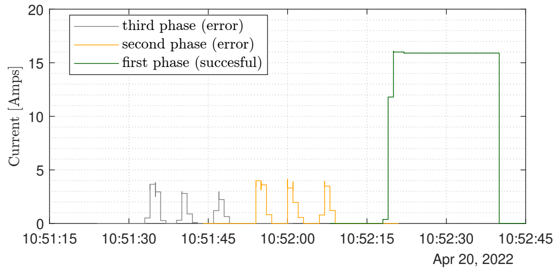


Fig. 13: Testing the ability to charge on single phase for Renault Zoe.

It is important to note that EV manufacturers that design three-phase charging vehicles offer the possibility of charging in a single phase through the first phase of the on-board charger. Here, when the phase switch occurs, the manufacturers consider the vehicle to be a single phase. Thus, manufacturers follow the standard that the single-phase charging vehicle should charge through the first phase (visually observed as L1 of the Type 2 charging cable). Furthermore, Table I summarizes the results from the testing procedure. Here for the Zaptec chargers, we also include results from [19] in order to better evaluate latencies subject to the cloud or the charger itself.

TABLE I: KPI results from charging test. The current modulation resolution refers to smart chargers. The accuracy column refers to the EV on-board charger. PWM delay reflects the time gap from the human operator entering a duty-cycle to the smart charger transmitting the duty-cycle to the vehicle. Time delay refers to the vehicle on-board charger from receiving the control pilot to starting the charging process.

Charger	**EV**	**Current modulation**	**Accuracy [Watt]**	**PWM delay [s]**	**Time delay [s]**	**3-1 switch phase**
Zaptec	Tesla P 85 kWh	0.1 Amps	$\sim \pm 300$	~ 0.4	~ 4	Yes
	Zoe 41kWh	0.1 Amps	$\sim \pm 400$	~ 0.4	~ 4	Yes
ACDC	Zoe 41kWh	0.06 Amps	$\sim \pm 400$	~ 0.1	~ 4	Yes
	LEAF 24kWh	0.06 Amps	$\sim \pm 100$	~ 0.1	~ 1	-

The accuracy values of Renault Zoe exhibit the highest accuracy when the vehicle is in low SOC. This has been shown previously in Figs.6 and 7. The PWM delay is measured using an oscilloscope and the time delay using DEIF smart meters (Table I). For changes in the PWM signal, the IEC 61851 standard requires a time delay of less than five seconds, which is the case for all tested EVs. However, the results point out that the delay from the chargers is quite small (400 ms and 100 ms) when compared to the EV on-board chargers (1 to 4 sec).

V. CONCLUSIONS

This paper introduced a feature assessment of differently controlled (centralized and distributed) state-of-the-art smart chargers. First, the chargers were tested for potential peak-shaving, valley-filling, and phase-balancing actions. Second, by utilizing KPIs such as accuracy, time delay, and precision the manuscript evaluates the smart chargers and available EVs on-board charger. The results of both smart chargers show a successful execution of the smart actions mentioned above. Charge modulation is successful and relatively fast and precise when tested with Tesla Model S, Renault Zoe, and Nissan LEAF. Furthermore, the three-phase EVs can charge in a single phase; however, that single phase must be the first phase of the on-board charger.

The current modulation resolution is 0.1 Amps and 0.06 Amps for Zaptec and ACDC charger, respectively. In terms of the precision of charging power (following the PWM signal), it is correlated with the vehicle SOC. For a high SOC, the vehicle requires less charging current, thus, the precision deteriorates. Renault Zoe suffers the most from lack of precision due to the SOC, while Tesla Model S P85 comes second and Nissan LEAF is the best from three tested EVs. With respect to time delay, the downward modulation is faster than upward modulation. The reason is that upward modulation is subject to the vehicle on-board charger dynamics and the lack of constraints in the IEC 61851 charging standard. Finally, accuracy is the sole responsibility of the vehicle's on-board charger, as smart charger manufacturers incorporate very accurate oscillators in their chargers. Nissan LEAF is the fastest and most accurate of the tested vehicles. Overall, all tested EVs respond within the five seconds requirement for changing charging current. However, the speed of response of the EVs on-board charger is the bottleneck to providing faster ancillary service. The results presented in this article help to better simulate the charging behavior for future dynamic investigations. For future work, it is necessary to understand the sub-second time delays for both chargers. To do so, it will require higher resolution meters. In addition, a larger testing of different EV manufactures need to take place in order to recognize the behavior of such vehicles.

Acknowledgement

The work in this paper is supported by the research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092). Website: www.acdc-bornholm.eu and www.fuse-project.dk.

References

[1] M. Marinelli, L. Calearo, S. Ried, X. Pfab, J. C. D. Cabrera, C. Spalthoff, M. Braun, H. Sale, B. N. Torsater, P. H. Divshali, S. Hanninen, M. Ceraolo, S. Barsali, M. Larsson, A. Magdowski, L. Gimenez, and G. Fernandez, "Electric Vehicles Demonstration Projects-An Overview across Europe," *UPEC 2020 - 2020 55th International Universities Power Engineering Conference, Proceedings*, 2020.

[2] G. Pasaoglu, D. Fiorello, A. Martino, G. Scarcella, A. Alemanno, A. Zubaryeva, and C. Thiel, *Driving and parking patterns of European car drivers - a mobility survey*. 2012.

[3] M. Muratori, "Impact of uncoordinated plug-in electric vehicle charging on residential power demand," *Nature Energy*, vol. 3, no. 3, pp. 193–201, 2018.

[4] S. Habib, M. M. Khan, F. Abbas, L. Sang, M. U. Shahid, and H. Tang, "A Comprehensive Study of Implemented International Standards, Technical Challenges, Impacts and Prospects for Electric Vehicles," *IEEE Access*, vol. 6, pp. 13866–13890, 2018.

[5] E. Dudek, "The Flexibility of Domestic Electric Vehicle Charging: The Electric Nation Project," *IEEE Power and Energy Magazine*, vol. 19, no. 4, pp. 16–27, 2021.

[6] M. Z. Degefa, I. B. Sperstad, and H. Sæle, "Comprehensive classifications and characterizations of power system flexibility resources," *Electric Power Systems Research*, vol. 194, no. January, p. 107022, 2021.

[7] L. Calearo, M. Marinelli, and C. Ziras, "A review of data sources for electric vehicle integration studies," *Renewable and Sustainable Energy Reviews*, vol. 151, no. December 2020, 2021.

[8] A. Thingvad, P. B. Andersen, T. Unterluggauer, C. Træholt, and M. Marinelli, "Electrification of personal vehicle travels in cities - Quantifying the public charging demand," *eTransportation*, vol. 9, p. 100125, 2021.

[9] J. Bollerslev, P. B. Andersen, T. V. Jensen, M. Marinelli, A. Thingvad, L. Calearo, and T. Weckesser, "Coincidence Factors for Domestic EV Charging from Driving and Plug-in Behavior," *IEEE Transactions on Transportation Electrification*, vol. 7782, no. c, pp. 1–1, 2021.

[10] F. G. Venegas, M. Petit, and Y. Perez, "Plug-in behavior of electric vehicles users: Insights from a large-scale trial and impacts for grid integration studies," *eTransportation*, vol. 10, p. 100131, 2021.

[11] J. Hildermeier, C. Kolokathis, J. Rosenow, M. Hogan, C. Wiese, and A. Jahn, "Smart ev charging: A global review of promising practices," *World Electric Vehicle Journal*, vol. 10, no. 4, pp. 1–13, 2019.

[12] K. Sevdari, L. Calearo, P. B. Andersen, and M. Marinelli, "Ancillary services and electric vehicles: an overview from charging clusters and chargers technology perspectives," *Renewable and Sustainable Energy Reviews*, vol. 167, p. 112666, 2022.

[13] International Electrotechnical Commission, "IEC 61851." https://webstore.iec.ch/publication/33644, 2017. Accessed: 19.03.2022.

[14] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki, "Taxonomy for evaluation of distributed control strategies for distributed energy resources," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5185–5195, 2017.

[15] K. Sevdari, L. Calearo, S. Striani, P. B. Andersen, M. Marinelli, and L. Rønnow, "Autonomously distributed control of electric vehicle chargers for grid services," in *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, pp. 1–5, IEEE, 2021.

[16] S. Striani, K. Sevdari, Y. Kobayashi, K. Suzuki, and M. Marinelli, "Autonomously distributed control of ev parking lot management for optimal grid integration," in *International Conference on Renewable Energies and Smart Technologies (IC-REST)*, 2022.

[17] P. Richardson, D. Flynn, and A. Keane, "Local versus centralized charging strategies for electric vehicles in low voltage distribution systems," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 1020–1028, 2012.

[18] L. Calearo, K. Sevdari, and M. Marinelli, "Status e-mobility DK," tech. rep., DTU – Technical University of Denmark, 2021.

[19] V. C. Foss and R. M. Knudsen, "Smart from Start Experimental Validation of Dynamic Charging Limits via EVSE," tech. rep., Bsc in Electrical Engineering, DTU, 2021.

[20] V. Foss and R. Meier, "Development of Harmonized Tests for Smart Electric Vehicle Charging across Charging Equipment," tech. rep., Special Course report, DTU, 2021.

[21] S. Jakobsen, L. Flader, P. B. Andersen, A. Thingvad, and J. Bollerslev, "Sådan skaber danmark grøn infrastruktur til én million elbiler: Analyse og anbefalinger fra dea og dtu, november 2019," 2020.

[22] O. Gehrke, C. Ziras, K. Heussen, T. V. Jensen, and H. W. Bindner, "Testbeds for active distribution networks: Case experience from syslab," 2021.

[23] S. Yumiki, Y. Susuki, Y. Oshikubo, Y. Ota, R. Masegi, A. Kawashima, A. Ishigame, S. Inagaki, and T. Suzuki, "Autonomous Vehicle-to-Grid Design for Provision of Frequency Control Ancillary Service and Distribution Voltage Regulation," *Sustainable Energy, Grids and Networks*, vol. 30, p. 100664, 2021.

[24] M. B. Anwar, M. Muratori, P. Jadun, E. Hale, B. Bush, P. Denholm, O. Ma, and K. Podkaminer, "Assessing the value of electric vehicle managed charging: a review of methodologies and results," *Energy & Environmental Science*, vol. 15, no. 2, pp. 466–498, 2022.

PAPER [P6]

Aggregation and control of electric vehicles AC charging for grid services delivery

Authors:

Kristian Sevdari, Peter Bach Andersen, Mattia Marinelli

Submitted to:

IEEE Transactions on Smart Grid

Aggregation and control of electric vehicles AC charging for grid services delivery

Kristian Sevdari, *Graduate Student Member, IEEE*, Peter Bach Andersen, *Member, IEEE*, and Mattia Marinelli, *Senior Member, IEEE*

***Abstract*—The mass electrification and penetration of converter based renewable energy source (RES) challenges the conventional stability and operation of the power grid. Therefore, the power grid necessitates the support of flexible and controllable demand side units. Here, a synergy between electric mobility and RESs can contribute significantly to the progress of both industries. This article presents a novel methodology and results for measuring, controlling, and aggregating the electric vehicle (EV) AC slow charging. The investigation contributes to quantify the entire control loop to deliver a grid service with EVs. Over-the-air communication is measured to be from 0.37 to 10 seconds. In addition, the dynamic charging behaviors (ramp rates and delays) of EVs are modeled. Ramp rates are asymmetric, and the largest delay is the initial start-charging delay. Tesla vehicles experience the largest asymmetry, where ramp up is as slow as 0.73 [kW/s], while ramp down is as fast as 552 [kW/s]. Depending on the characteristics of the vehicle model, it is possible to achieve subsecond grid service delivery. Finally, the article demonstrates the simulated power demand from 100 EVs, emphasizing the uncertainties and the imperative for aggregators to understand their aggregated resources, including vehicle types.**

***Index Terms*—Aggregation, Control, Electric vehicles, Smart charging, Grid services.**

I. Introduction

A. Background

THE increased penetration of converter based RES demands new ways to maintain the stability of the electric power grid. Thus, joint recent work from IEEE PES and CIGRE [1], has revisited the power system stability conundrum and extended the dynamic behavior traditionally dominated by fairly slow synchronous generators and their controllability, to fast transients induced by power converters. First, the lack of inertia and the variability of converter-based RES are particularly challenging for normal power system operation [2]. Second, the phase-out of the controllable thermal units and the decrease of load damping effect [3] necessitates the support from flexible demand side units [4]. However, the need for demand-side flexibility is required both on a large (system-wide) and small (local grid) scale [5], due to the large penetration of distributed technologies (generation and demand) in distribution grids. While variable distributed energy resources (DERs) require flexibility from the demand side to match their production, the demand electrification uptake calls for a flexible consumption pattern to not overload the electrical grid [6].

Manuscript created August 2023; The work in this article is supported by the Danish research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092). *Corresponding author: Kristian Sevdari*

K. Sevdari, P.B. Andersen, and M. Marinelli are with the Division for Power and Energy Systems, Department of Wind and Energy Systems, Technical University of Denmark (DTU), Roskilde, Denmark.

B. Motivation

Demand response programs aim to harvest flexibility from end users for i) grid; ii) economic; and iii) socio-environmental oriented benefits [7], [8]. The authors of [9], [10] have acknowledged the great techno-economic benefits of demand-side flexibility. However, one of the main barriers is the ability to integrate and coordinate the operation of DERs. EVs are a promising demand response technology [11] that can provide flexibility by modulating, shifting, or switching the charging process [12]. However, to provide a grid service with EVs, control and aggregation between many entities should be carried out. Previous studies such as [13], [14] have described the different control approaches for DERs, such as centralized, distributed, or decentralized. A more specific overview of electric mobility can be found at [15], while a summary of grid services and the advantages or drawbacks of centralized, decentralized, and distributed control approaches can be found at [16]. The main technical barrier to achieving reliable and fast large-scale control for EVs AC charging process remains the communication standards chosen from different vendors [17] and the onboard charger technology [18]. Here, driven by the high profitability of power reserve markets in the Nordics, Texas, Australia, Ireland, and the United Kingdom [19], many commercial EV aggregators are pushing to qualify for the very fast reacting frequency products (overall delay of 1-2.5 s). Such requirements, although strict in the overall control loop speed, have been proven to be crucial and beneficial to the stability of the power system with a high penetration of RESs [20]. In addition to participating in the balancing services market, large-scale coordination of EVs from commercial aggregators is becoming techno-economically beneficial even for wholesale energy and local flexibility markets [21]. Therefore, the overall needs for grid services can range from milliseconds to days [4].

C. Contributions

Figure 1 gives a detailed description of the communication paths and respective standards that can be used for the provision of grid services with EVs. The literature review [16], [22], [23] suggests that most of the research for the provision of grid services with EVs remains on theoretical or simulation ground. Those who expand their investigation even to the physical domain are mainly interested in charging technology [24], and not the aggregation and control of large clusters of charging technology. Few examples have attempted to understand the overall control loop [25], [26], however, without proper investigation of the control challenges of each device and communication challenges. Subsequently, most investigations explore the controllability of electric vehicle supply equipment (EVSE) and EV through the ChadeMO standard for vehicle-to-grid (V2G) applications [25]–[27]. Field testing in Denmark for DC V2G with the ChadeMO standard has concluded that V2G-EV setup experience on average 6-8 s of control delay [20].

However, our investigation, due to their large deployment, is focused on the AC charging mode, which is based on the IEC 61851 standard. To achieve the provision of grid service with EVs in AC charging mode, several steps must be followed. For example, to deliver a frequency service to transmission system operator (TSO), the control command will start from the aggregator to charging point operator (CPO) followed by the EVSE manufacturer cloud to EVSE and the vehicle itself. Here, it is necessary to distinguish two communication paths. On the one hand, there is over-the-air communication between the aggregator-CPO-EVSE. On the other hand, there is physical communication between EVSE-EV. Open charge point protocol (OCPP) is the protocol most commonly used for over-the-air communication. While IEC 61851 is the standard that defines the communication between EVSE and onboard charger (OBC) of EV.

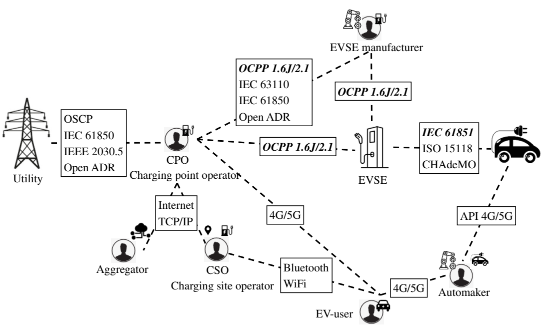


Fig. 1: Communication standards for delivering grid services, inspired from [17], [18].

The contributions of this article are as follows.

- Developing and validating a methodology to investigate control delay and ramp rates for single or clusters of EVs during AC charging.
- Evaluating the delay in over-the-air communication between the aggregator or CPO with EVSE.
- Evaluating the response delay from EV to the control action provided by EVSE through IEC 61851.
- Modeling the response and ramp rates of EV OBC.
- Demonstrating fast frequency service and uncertainty of aggregation with EVs.

The remainder of the manuscript is structured as follows. Section II presents the novel scientific method for field testing the AC smart charging control delays and ramp rates for vehicle OBC. Consequently, Section III introduces the results of the test campaign and the demonstration case. Finally, Section IV concludes the article with the main findings.

II. Methodology

A smart EVSE (or smart charger) is required to enable grid service provision with EVs. Previously, in Ref. [28], the definition of smart EVSE was presented and reads as follows. *Smart charger is an electric device providing protection, communication, at least scheduling and at most modulation, phase curtailment (3 to 1-phase switch) and phase switching for the EV charging process.* Therefore, it is of paramount importance to understand the communication delays and dynamic behavior of EV OBC.

This paper proposes a methodology to fully understand the dynamical behavior and cloud constraints of providing grid services with AC smart chargers. Figure 2 provides a detailed description of the research methodology and the test setup built in our DTU-EV laboratories.

In Fig. 2 on the left is the Labcell supplying the smart charger with a maximum of 32 A via a CEE plug. The smart charger is connected to the EV via the Type 2 cable. The human operator, according to IEC 61851, can modulate the charging limit (I_{ch}) by changing the duty cycle (D) of pulse-width modulation (PWM) control pilot: $I_{\mathrm{ch}} = \mathrm{D} \times 0.6Amps$.

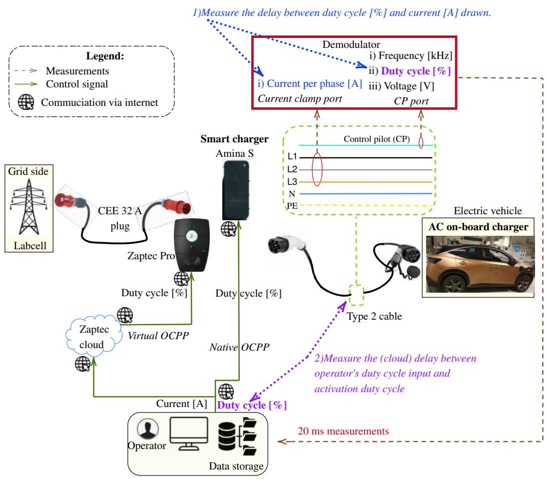


Fig. 2: Methodology to quantify and model the cloud and EVs on-board charger dynamic behavior.

Zaptec Pro (smart charger) is a representative of cloud OCPP, while Amina S (smart charger) is a representative of native OCPP. In the former, the control action follows the operator- EVSE manufacturer cloud-EVSE path. In the latter case, the control action is more direct from the operator to EVSE. The novel approach in the research methodology is the ability to measure every signal that passes through the Type 2 cable. That is achieved via the demodulator built specifically for this application.

The demodulator has two ports: i) the current clamp port and ii) the control pilot (CP) port. The current clamp port measures the current [A] flowing in each phase (L1, L2 and L3) to charge the EV. The CP port measures the i) frequency [kHz], ii) duty cycle [%], and iii) voltage of the PWM control signal. All the measurements are recorded on the same epoch timescale every 20 ms. The ability to measure every signal on the same timescale together with the operator input signal allows us to evaluate the communication delays of 1) the vehicle OBC and 2) the over-the-air or operator-EVSE path.

The IEC 61851-1 standard demands the following relevant EVSE timings. t_{external} is the maximum allowed response time (10 s) for an external command, which may be a manual setting or a command from the grid management systems to EVSE. t_{ichange} is the maximum time allowed (5 s) vehicle OBC to change the charging current after a change in PWM duty cycle. Therefore, to react for a new control set point from the aggregator (operator) to EVSE and EV the IEC 61851-1 standard allows up to 15 s of delay. As discussed previously, such a delay is too large for fast-acting actions required from a variable RES dominated power system.

This article provides valuable knowledge for the first time by measuring practical t_{external} and t_{ichange}. Here, t_{ichange} is only related to vehicle OBC and may differ from one automaker to another. Instead, depending on the communication and control approach chosen (distributed, decentralized or centralized), t_{external} can face different delays. Figure 3 explains the overall differences in the control scheme and visualizes the contributions of the article in terms of understanding the physical t_{external} and t_{ichange} delays.

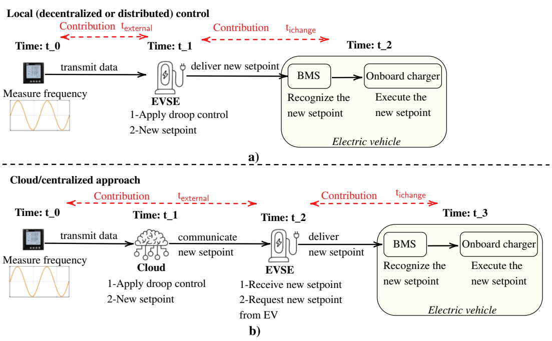


Fig. 3: Visualization of the delays when offering a grid service (frequency regulation example) with EVs.

The example includes delivering of frequency service to TSO. In this case, theoretically, the local control approach offers a shorter delay compared to the centralized approach. However, the cost of having local meters is higher in the local approach when compared with the centralized approach, which only requires a single measurement point. Moreover, while frequency services are highly demanding on the control timescale (fast phenomenon), other grid services, such as voltage regulation or congestion management, are slower phenomena. Lastly, due to the ability of the demodulator (Fig. 2) to measure the charging current on a 20-ms timescale, we measure the dynamical behavior (ramp rates) of the vehicle OBC.

III. Aggregation and Modeling

This section presents the results for t_{external} (delay between CPO and EVSE) and t_{ichange} (delay between EVSE and EV).

A. EVSE charging dynamics

The smart EVSE testing sample consists of ACDC, Keba P30, Zaptec Pro, and Wattpilot 22. These EVSEs represent different control approaches as explained below:

- ACDC : The operator interfaces to the EVSE.
- Keba P30: The operator interfaces via OCPP 1.6J (native OCPP) to the EVSE.
- Zaptec Pro: The operator relies on the OCPP protocol with the Zaptec backend (virtual OCPP), and the Zaptec server communicates with EVSE.
- Wattpilot 22: The operator communicates locally through WiFi with EVSE.

Figure 4 displays the reaction speed of Wattpilot 22 from the moment the operator sends a control command. The operator reduces the charging current from 32 A (53.3% duty cycle) to 6 A (10 % duty cycle) and vice versa. The time between the operator changing the charging current and EVSE reflecting the new set point is measured. Since Wattpilot is tested by WiFi communication, the distance between the devices was not more than five meters.

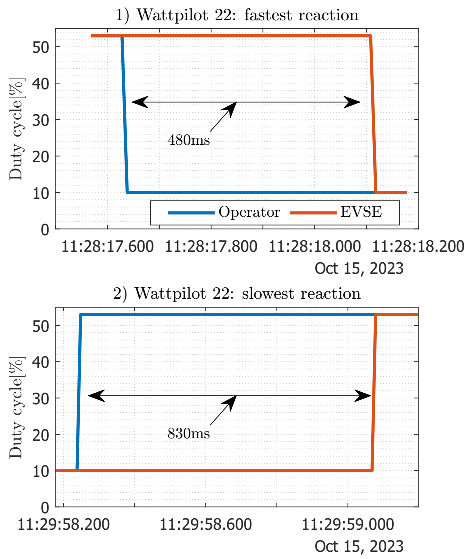


Fig. 4: Operator to Wattpilot reaction delay.

Moreover, Table I summarizes the results for tested EVSEs. One can observe that Zaptec Pro is faster than other EVSE. Keba P30, which employs OCPP 1.6J, is the slowest of the test samples. ACDC control topology slightly resembles that of Zaptec, however, it is slower in response time. Alongside the fastest and slowest time in Table I, the median delay is presented. This delay value is more important to properly modelling the t_{external}.

TABLE I: t_{external} for different EVSE brands and control methodologies.

Delay	ACDC	Keba P30	Zaptec Pro	Wattpilot 22
Slowest [s]	1.8	15.7	0.55	0.83
Fastest [s]	0.95	10	0.37	0.48
Median [s]	1.6	14	0.4	0.7

B. Electric vehicle charging dynamics

As previously mentioned, the third and fourth contributions of our investigation are about the delays and ramp rates experienced in the vehicle OBC. Figure 5 provides detailed visualizations of key performance indicators (KPIs) used to measure the charging dynamics of vehicle OBC. Ramp-up rate is the variable measured in [A/s] or [kW/s] that describes the OBC rate limitations for drawing current. The values are measured in A/ms; however, for better understanding it is converted to A/s. Similarly, the ramp-down rate measures the rate of reduction of the charging current.

Furthermore, t_a is the time that vehicle OBC needs to wake up from a non-charging position (0 A). t_b is the time required to go from zero to full charging current. t_c is the OBC delay to respond to a received command (decrease charging current) during the operation mode. t_d is the time needed to go from full charging amps to the minimum allowed charging current (6 A). t_e is the OBC delay to respond to a received command (increase charging current) during the operation mode. t_f is the time needed to go from the minimum allowed charging current (6 A) to full charging amps. Lastly, t_g is the time required to go from full charging current to zero. Hence, t_{ichange} should differ during the charging state as follows:

- Charging start up or state change from connected (B) to charging (C) : $t_{\text{ichangestart}} = t_a$
- Charging ramp down: $t_{\text{ichangerd}} = t_c$
- Charging ramp up: $t_{\text{ichangerp}} = t_e$
- Charging stop: $t_{\text{ichangestop}} = t_c$

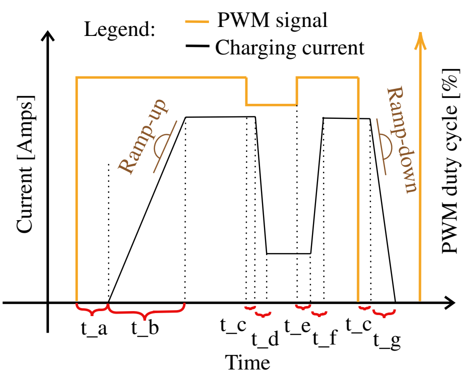


Fig. 5: Visualization of the KPIs used for the EV charging dynamics.

Moreover, Figs. 6 and 7 provide a detailed graph for the dynamics of the Nissan ARIYA charging process. The left and right y-axes display the duty cycle [%] and the charging current [A] of the first-phase, respectively. The data are recorded on a 20-ms scale. Additionally, the plotted graphics reflect the discrete nature of the measurement.

Observing the start up charging state (see Fig. 6), one can clearly spot the EV OBC dynamics. Nissan ARIYA OBC reacts 500 ms after receiving the command to start charging. This moment, according to IEC 61851-1, reflects the change in the states from connected (state B) to charging (state C). The change in states (from B to C) accounts for the largest delay in the charging dynamics. This is similar for all vehicles tested. Once the vehicle enters state C (charging), it becomes more responsive. For example, t_c and t_e of the Nissan ARIYA are around 20 ms. Nissan ARIYA (2022) version 87 kWh requires around four seconds to reach zero to maximum charging current. Furthermore, Fig. 6 presents the stopped charging dynamics. Here, there are two options to achieve this. The first option is to provide a duty cycle outside of 10-80 % or open the EVSE relays de-energizing the OBC. While the latter is faster to stop a charging session, it suffers from a longer delay if the charging session needs to be restarted. Nissan ARIYA (2022) version 87 kWh requires around 1.5 seconds to reach maximum to zero charging current.

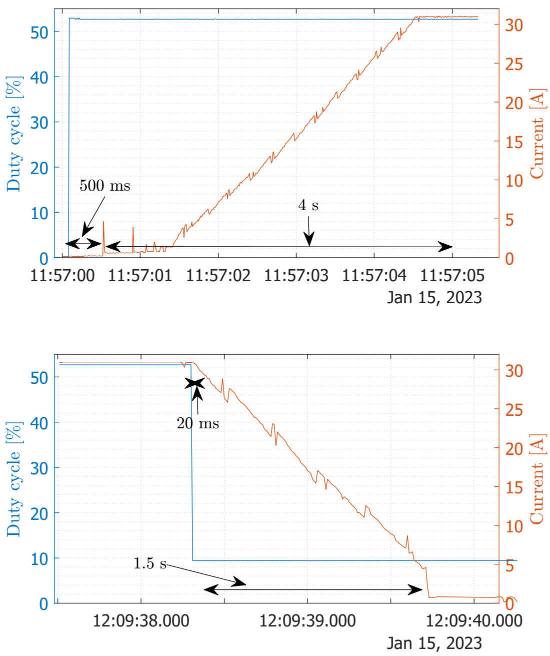


Fig. 6: Nissan ARIYA (2022) start up (top) and stop (down) charging states.

Moreover, Fig. 7 describes the delays and dynamics of ramping-up and down during the charging process. The ramp-up and down values are measured for the six- to maximum [A] charge current and the maximum to six [A] charging current per phase, respectively. Nissan ARIYA displays a 9.55 [A/s] ramp up and an almost twice faster ramp down 18.2 [A/s]. This asymmetric behavior is common for tested vehicles and

TABLE II: Modeling data for electric vehicle onboard charger based on field validations.

Vehicle	Max/min ch.current	Ramp-up per phase [A/s]	Ramp-up [kW/s]	Ramp-down per phase [A/s]	Ramp-down [kW/s]	t_a [s]	t_b [s]	t_c [s]	t_d [s]	t_e [s]	t_f [s]	t_g
VW ID3 Pro (2023) 58 kWh	16/6	14.54	10.03	114.28	78.85	2.54	1.1	0.78	0.14	0.78	0.94	0.14
Nissan Arya (2022) 87 kWh	32/6	9.55	6.59	18.2	12.55	0.5	4	0.02	1.35	0.02	2.55	1.5
Nissan LEAF e+ (2022) 62 kWh	32/6	25	5.75	21.8	5.01	3.6	1.28	0.03	1.19	0.03	1.05	0.23
Skoda Enyaq iV 60 (2021) 62 kWh	16/6	13.3	9.17	160	110.4	2	1.2	0.68	0.1	0.68	0.84	0.1
Tesla M3 LRDM (2020) 78.1 kWh	16/6	1.06	0.73	800	552	2	15	0.02	0.02	0.02	8	0.02
Renault Zoe 40 (2018) 44.1 kWh	32/6	8.8	6.13	40	27.6	3.8	3.6	0.1	1.25	0.65	2.78	0.5

answers the question of why previous demonstrations could not manage symmetric behavior [29].

Table II summarizes the results of the vehicles tested.

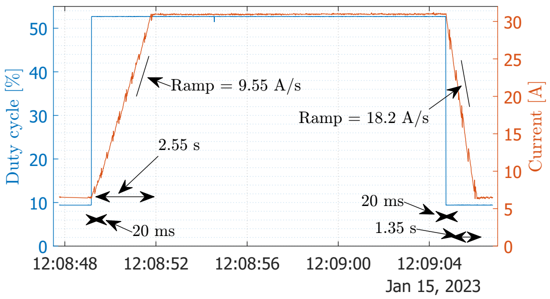


Fig. 7: Nissan ARIYA (2022) ramp up and down charging dynamics.

As the data suggest, t_a is the longest delay and corresponds to the change in the charging states from connected (B) to charging (C). The IEC 61851-1 standard demands that the reaction to a set point (t_{ichange}) not exceed four seconds. This is confirmed by all vehicles tested. t_c and t_e are in the same range for the vehicle tested. Table II also provides ramp up and down values in kW/s for easier understanding. Here, it can be seen that the asymmetric behavior is a common feature. The Nissan brand is much closer to having a symmetric behavior.

C. Aggregation of charging dynamics

Measurement and visualization of individual OBC charging dynamics helps to better understand the cluster or aggregated charging dynamics. Figure 8 (top) provides data on how different EV brands start their charging process. Renault Zoe brand, which employs a Chameleon integrated OBC charger, is the fastest among the vehicles tested. In addition, one can observe that Chameleon chargers have been improving their speed in the newer generations. Zoe 20 is the first generation, Zoe 40 is the second generation, and Zoe 50 is the third generation. Here, one can observe that Tesla OBC is the slowest among the tested vehicles. Long delays and slow Tesla ramp-up OBCs are some of the reasons why aggregators have not been able to provide fast grid services to grid operators in pilot demonstrations.

Furthermore, Figs. 8 (middle) and (bottom) demonstrate the large uncertainty of OBCs dynamics when starting the charging process of 100 EVs. Depending on the dominant EV the saturated active power consumption can vary from 1084 to 1522 kW (40%) at 16:06:48, see Fig. 8 (middle). In addition, the speed to reach saturated charging power depends on the type of vehicles in the pool. For example, Zoe 50 is the fastest ramp-up vehicle. When the pool of EVs is dominated by Zoe 50, the aggregated charging dynamics are much faster compared to slower EV models.

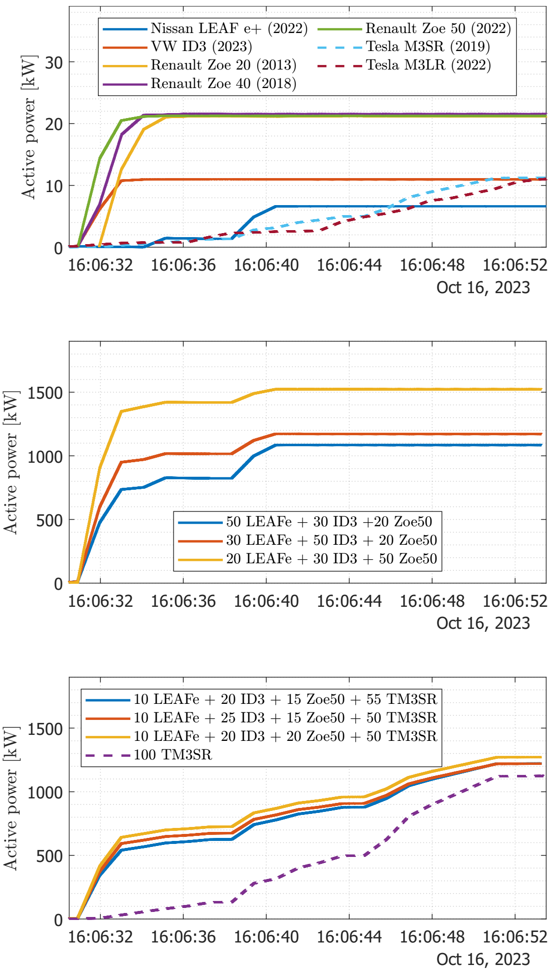


Fig. 8: Charging start up dynamics for single EVs (top), aggregation of EVs with Nissan LEAF e+, VW ID3 and Renault Zoe 50 (middle), aggregation of EVs with Nissan LEAF e+, VW ID3, Renault Zoe 50 and Tesla Model 3 (bottom).

The difference after six seconds (16:06:30-16:06:36 Fig. 8 (middle)) is 823 to 1419 kW (72%). The uncertainty of the charging power is greater before the saturation of the charging power. This is the case even when to the pool of EVs is added Tesla Model 3 vehicles, see Fig. 8 (bottom). The uncertainty of saturated power is smaller (1121 to 1271 kW, or 13%) when one type of EV dynamic is dominant; see Fig. 8 (bottom) at 16:06:52. Moreover, Fig. 8 (bottom) displays the difference in aggregating 100 homogeneous Tesla Model 3 EVs with a heterogeneous cluster of EVs still dominated by Teslas. An aggregator entity should develop a good understanding of its EV resources to construct an area of up and lower limits for its charging power demand aggregation. For example in Fig. 8 (bottom), 100 homogeneous Tesla Model 3 EVs serve as the low boundary and the heterogeneous cluster (10 Nissan LEAF e+, 20 VW ID3, 20 Renault Zoe 50 and 50 Tesla Model 3 Standard Range) as the upper boundary. This particle knowledge is crucial for the pre-saturated charging power, which stretches up to 16 seconds. The relatively large timescale compromises most of fast delivery grid service products. Therefore, aggregator entities should strive to have knowledge of their aggregated resources, such as vehicle model.

D. Control of aggregated EVs for delivery of frequency services

The delivery of a frequency service (for example frequency containment reserve for disturbance operation (FCR-D)) requires a relatively fast control approach. According to the Nordic regulation, the injected power should be greater than zero at 2.5 seconds and the full bid delivery at 7.5 seconds [30]. The minimum market size for a commercial aggregator entity to enter the FCR-D market in Denmark is 100 kW. Therefore, it is necessary to aggregate multiple EVSEs to satisfy the market bid requirement. Consequently, this becomes challenging when multiple clusters of EVSE are controlled to provide a frequency service. The combination of entire control loop delays is necessary to initially fulfill the 2.5 second requirement and the ramping rates satisfy the 7.5 second requirement. Figure 9 summarizes the demonstration results of the FCR-D pre-qualification process with a centralized control approach using ACDC smart EVSE and two identical Renault Zoe 40.

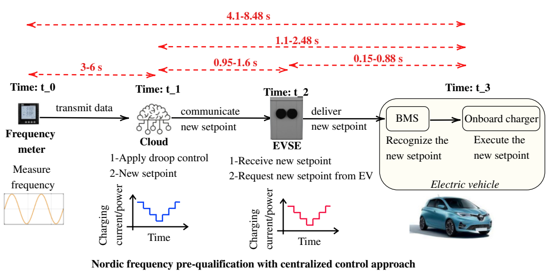


Fig. 9: Demonstration of Nordic frequency service delivery pre-qualification process with a cluster of chargers and two homogeneous Renault Zoe 40.

In agreement with the data, controlling a cluster of EVSEs adds more delays to the control loop compared to controlling a single EVSE. The current ACDC cloud setup takes up to six seconds to receive and calculate new active power setpoints for the charging cluster. The majority of that delay (six seconds) is due to not yet optimized control algorithms and communication with external servers in the cloud intelligence. However, the overall control delay from measuring a frequency deviation to injecting power can extend from 4.1 to 8.48 seconds. Looking at the delay between the cloud communicating a new power set point and the vehicle responding, it stretches between 1.1 and 2.48 seconds. Here, the small response delay of the vehicle OBC corresponds to modulating up or down 2 [A]. Consequently, this proves that, with an optimized cloud computing system, it is possible to achieve FCR-D delivery with Renault Zoe 40.

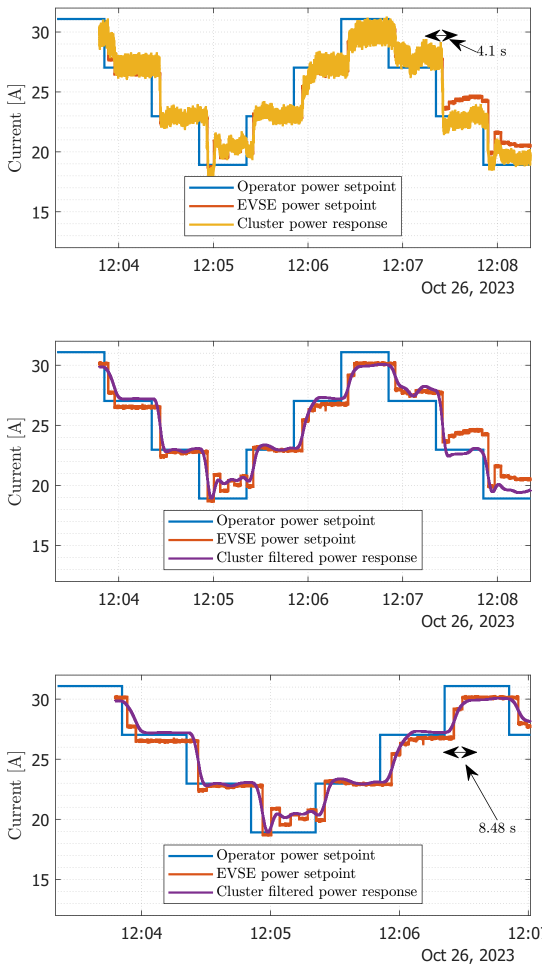


Fig. 10: Demonstration of Nordic frequency service delivery pre-qualification process with a cluster of chargers and two Renault Zoe 40. Raw plotted data (top), filtered plotted data (middle), and filtered data zoomed in a single FCR-D delivery cycle (bottom).

Figure 10 plots the results of the test sequence. The cluster provides 4 [A] or 2.76 [kW] per 0.1 Hz step. As mentioned above, OBC suffer from asymmetric ramp rates and sometimes even reaction delays. Hence, providing frequency up-regulation (increasing consumption) is faster than providing frequency down-regulation (reducing consumption). Due to homogeneity, the typical behavior of a single Renault Zoe 40 is reflected in the cluster dynamics. On the one hand, the fastest reaction time (4.1 seconds) is reached when providing down modulation; see Fig. 10 (top) at 12:07:21. On the other hand, the slowest reaction time (8.48 seconds) is achieved when providing up modulation; see Fig. 10 (bottom) at 12:06:23.

Moreover, when providing a frequency service, it is important to meet the time delivery requirements in the up-and-down modulation. In addition, the cluster should match the power response with the bid size offered in the market. Here, another challenge arises due to the uncertainty in the IEC 61851-1 standard. The standard communicates a limit charging current / power, while it is the vehicle battery management system (BMS) that decides the exact charging current / power for the vehicle. The values of EVSE and BMS may differ when the vehicle is closer to a high state-of-charge (SOC), thus resulting in a possible active power under-delivery.

IV. Conclusions

This manuscript presented a novel method to investigate and measure control delays for single or clusters of EVs during AC charging. The control delay between an aggregator entity (such as a CPO) and the EV can be divided into two parts. The delay between CPO-EVSE and EVSE-vehicle OBC. The former relies on the quality of the EVSE manufacturer, CPO backend applications and the standard communication limitations. The latter relies on the technological improvements from automakers.

The IEC 61851-1 standard demands 10 s for the maximum allowed response time (t_{external}) for an external command, which may be a manual setting or a command from the grid management systems to EVSE. Three different EVSE communication topologies (WiFi, OCPP and 4G) are tested and measured against their reaction speed. The data suggest that OCPP 1.6J communication might be delay-prone due to heavier data transactions and security. However, the results show that it is possible to reach a delay below 1 second between CPO-EVSE. In particular, if CPO wants to provide grid service by stopping charging operations, it can be achieved by controlling EVSE in less than 0.5 seconds. However, restarting the charging process would require significantly more time.

Furthermore, the IEC 61851-1 standard requires that the maximum allowed time is five seconds for vehicle OBC to change the charging current after a change in PWM duty cycle (t_{ichange}). All tested vehicles meet this requirement, where the largest delay is the charge-start process delay. Here, for the first time, the dynamic behavior (ramp rates and delays) of EV AC charging process is modeled.

The ramp rates [kW/s] of OBC are asymmetric. The ramp down is higher than the ramp up. Tesla vehicles experience the largest asymmetry, where ramp up is as slow as 0.73 [kW/s], while ramp down is as fast as 552 [kW/s]. The change in states from connected (B) to charging (C) accounts for the largest delay (second scale) in the charging dynamics. This is similar for all vehicles tested. Once the vehicle enters state C (charging), it becomes more responsive (millisecond scale).

Moreover, the manuscript presented the outcome of FCR-D pre-qualification process with ACDC smart EVSE and two identical Renault Zoe 40 for the Nordic synchronous area. The current setup offers a full control loop speed (CPO-EVSE-vehicle OBC) from 4.1 to 8.48 s. However, the response time from EVSE-vehicle OBC can stretch from 0.15 to 0.88 s. Therefore, it is possible to deliver fast grid services (below 1 second) with an optimized CPO control and communication system.

Finally, the article presented the simulated charging start of 100 EVs to showcase the uncertainty challenges related to aggregation or fleets. An aggregator entity should develop a good understanding of its EV resources (vehicle model) to construct an area of upper and lower limits for its charging power demand aggregation.

Lastly, future work should further investigate the evolution on AC charging dynamics of different brands and the same model over the years. In addition, a more thorough investigation is needed for the OCPP standard communication speed.

Acknowledgement

The work in this article is supported by the Danish research projects ACDC (EUDP grant number: 64019-0541) and FUSE (EUDP grant number: 64020-1092) The authors thank Oliver Gehrke for helping with such a testing campaign. The authors also thank Kristoffer Laust Pedersen and Pietro Zunino for helping with data analysis and test setup.

References

[1] N. Hatziargyriou, J. Milanovic, C. Rahmann, V. Ajjarapu, C. Canizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. Sanchez-Gasca, A. Stankovic, T. Van Cutsem, V. Vittal, and C. Vournas, "Definition and Classification of Power System Stability - Revisited & Extended," *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3271–3281, 2021.

[2] F. Milano, F. Dorfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems (Invited Paper)," *20th Power Systems Computation Conference, PSCC 2018*, pp. 1–25, 2018.

[3] H. Huang and F. Li, "Sensitivity analysis of load-damping characteristic in power system frequency regulation," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1324–1335, 2013.

[4] M. Z. Degefa, I. B. Sperstad, and H. Sæle, "Comprehensive classifications and characterizations of power system flexibility resources," *Electric Power Systems Research*, vol. 194, p. 107022, 2021.

[5] S. Chatzivasileiadis, P. Aristidou, I. Dassios, T. Dragicevic, D. Gebbran, F. Milano, C. Rahmann, and D. Ramasubramanian, "Micro-flexibility: Challenges for power system modeling and control," *Electric Power Systems Research*, vol. 216, no. September 2022, p. 109002, 2023.

[6] T. Unterluggauer, F. Hipolito, J. Rich, M. Marinelli, and P. B. Andersen, "Impact of cost-based smart electric vehicle charging on urban low voltage power distribution networks," *Sustainable Energy, Grids and Networks*, p. 101085, 2023.

[7] O. Ma, N. Alkadi, P. Cappers, P. Denholm, J. Dudley, S. Goli, M. Hummon, S. Kiliccote, J. MacDonald, N. Matson, D. Olsen, C. Rose, M. D. Sohn, M. Starke, B. Kirby, and M. O'Malley, "Demand response for ancillary services," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 1988–1995, 2013.

[8] M. E. Honarmand, V. Hosseinnezhad, B. Hayes, M. Shafie-Khah, and P. Siano, "An Overview of Demand Response: From its Origins to the Smart Energy Community," *IEEE Access*, vol. 9, pp. 96851–96876, 2021.
[9] M. Resch, J. Buhler, B. Schachler, and A. Sumper, "Techno-Economic Assessment of Flexibility Options Versus Grid Expansion in Distribution Grids," *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 3830–3839, 2021.
[10] J. Ostergaard, C. Ziras, H. W. Bindner, J. Kazempour, M. Marinelli, P. Markussen, S. H. Rosted, and J. S. Christensen, "Energy security through demand-side flexibility: The case of denmark," *IEEE Power and Energy Magazine*, vol. 19, no. 2, pp. 46–55, 2021.
[11] I. Safak Bayram, A. Saad, R. Sims, A. Babu, C. Edmunds, and S. Galloway, "Statistical Characterisation of Public AC EV Chargers in the UK," *IEEE Access*, vol. 11, no. July, pp. 70274–70287, 2023.
[12] K. Sevdari, S. Striani, P. B. Andersen, and M. Marinelli, "Power modulation and phase switching testing of smart charger and electric vehicle pairs," in *2022 57th International Universities Power Engineering Conference (UPEC)*, pp. 1–6, IEEE, 2022.
[13] P. Richardson, D. Flynn, and A. Keane, "Local versus centralized charging strategies for electric vehicles in low voltage distribution systems," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 1020–1028, 2012.
[14] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki, "Taxonomy for evaluation of distributed control strategies for distributed energy resources," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5185–5195, 2017.
[15] F. Gonzalez Venegas, M. Petit, and Y. Perez, "Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services," *Renewable and Sustainable Energy Reviews*, vol. 145, no. March, p. 111060, 2021.
[16] K. Sevdari, L. Calearo, P. B. Andersen, and M. Marinelli, "Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives," *Renewable and Sustainable Energy Reviews*, vol. 167, no. December 2021, p. 112666, 2022.
[17] Elaadnl, "EV related protocol study v1.1," no. January, 2021.
[18] S. Rivera, S. Kouro, S. Vazquez, S. M. Goetz, R. Lizana, and E. Romero-Cadaval, "Electric vehicle charging infrastructure: From grid to battery," *IEEE Industrial Electronics Magazine*, vol. 15, no. 2, pp. 37–51, 2021.
[19] D. Fernández-Muñoz, J. I. Pérez-Díaz, I. Guisández, M. Chazarra, and A. Fernández-Espina, "Fast frequency control ancillary services: An international review," *Renewable and Sustainable Energy Reviews*, vol. 120, p. 109662, 2020.
[20] M. Marinelli, K. Sevdari, L. Calearo, A. Thingvad, and C. Ziras, "Frequency stability with converter-connected resources delivering fast frequency control," *Electric Power Systems Research*, vol. 200, no. July, p. 107473, 2021.
[21] H. Patil and V. N. Kalkhambkar, "Grid Integration of Electric Vehicles for Economic Benefits: A Review," *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 1, pp. 13–26, 2021.
[22] O. Ardakanian, S. Keshav, and C. Rosenberg, "Real-time distributed control for smart electric vehicle chargers: From a static to a dynamic study," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2295–2305, 2014.
[23] M. K. Hasan, A. A. Habib, S. Islam, M. Balfaqih, K. M. Alfawaz, and D. Singh, "Smart Grid Communication Networks for Electric Vehicles Empowering Distributed Energy Generation: Constraints, Challenges, and Recommendations," *Energies*, vol. 16, no. 3, 2023.
[24] M. Restrepo, J. Morris, M. Kazerani, and C. A. Cañizares, "Modeling and testing of a bidirectional smart charger for distribution system EV integration," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 152–162, 2018.
[25] A. Zecchino, A. Thingvad, P. B. Andersen, and M. Marinelli, "Test and modelling of commercial V2G CHAdeMO chargers to assess the suitability for grid services," *World Electric Vehicle Journal*, vol. 10, no. 2, 2019.
[26] R. J. Askjar, P. B. Andersen, A. Thingvad, and M. Marinelli, "Demonstration of a Technology Neutral Control Architecture for Providing Frequency Control Using Unidirectional Charging of Electric Vehicles," *UPEC 2020 - 2020 55th International Universities Power Engineering Conference, Proceedings*, 2020.
[27] S. Saxena, H. Farag, K. Nasr, and L. S. Hilaire, "Field testing of residential bidirectional electric vehicle charger for power system applications," *arXiv preprint arXiv:2308.13624*, 2023.
[28] K. Sevdari, L. Calearo, B. H. Bakken, P. B. Andersen, and M. Marinelli, "Experimental validation of onboard electric vehicle chargers to improve the efficiency of smart charging operation," *Available at SSRN 4460277*, 2023.
[29] R. J. Askjær, P. B. Andersen, A. Thingvad, and M. Marinelli, "Demonstration of a technology neutral control architecture for providing frequency control using unidirectional charging of electric vehicles," in *2020 55th International Universities Power Engineering Conference (UPEC)*, pp. 1–6, IEEE, 2020.
[30] ENTSO-E, "Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area," no. January, p. 65, 2022.

Kristian Sevdari (Graduate Student Member, IEEE) was born in Kucove, Albania, in 1995. He received the B.Sc degree in electrical engineering from the Polytechnic University of Tirana in June 2016, and the M.Sc degree in electrical engineering from UiT Norges arktiske universitet in June 2020. Since 2020 he has been working toward the Ph.D. degree at DTU-Wind and Energy Systems, Denmark. His research interests include power system dynamics, renewable sources, and electric vehicle grid integration, as well as providing grid services from distributed energy resources.

Peter Bach Andersen (Member, IEEE) received the Ph.D. degree. He is currently a Senior Scientific Researcher with the DTU-Wind and energy Systems, part of the Technical University of Denmark, Roskilde, Denmark. His main research focuses on how grid integrated electric vehicles may support a stable, economic power system based on renewable energy. He was a Principle Investigator in a number of Danish research and demonstration projects. He is also a Board Member of the Danish EV Alliance, Trade organization and the advisory board of Copenhagen electric, the capital region of Denmark as to support national R&D efforts in this area.

Mattia Marinelli (Senior Member, IEEE) was born in Genoa, Italy, in March 1983. He received the B.Sc. and M.Sc. degrees in electrical engineering and the European Ph.D. degree in power systems from the University of Genoa, Genoa, Italy, in 2005, 2007, and 2011, respectively. Since September 2012, he has been with the Technical University of Denmark (DTU), Roskilde, Denmark, where he is currently an Associate Professor of distributed energy resources driven electric power systems. His research interests include power system integration studies, wind and solar data analysis, demand-side and electric vehicles management, and distributed energy resources modeling. Between 2015 and 2020, he was the Vice-Chair and then Chair for the PES chapter of the IEEE Denmark Section.

PAPER [P7]

Behind-the-meter residential electric vehicle smart charging strategies: Danish cases

Authors:

Mari Halldis Tveit, Kristian Sevdari, Mattia Marinelli, Lisa Calearo

Published in:

Proceedings of the 2022 International Conference on Renewable Energies and Smart Technologies (REST)

DOI:

10.1109/REST54687.2022.10022910.

2022 International Conference on Renewable Energies and Smart Technologies (REST) | 978-1-6654-0971-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/REST54687.2022.10022910

Behind-the-Meter Residential Electric Vehicle Smart Charging Strategies: Danish Cases

Mari Halldis Tveit
Division of Energy & Industry
Sweco Sverige AB
Malmö, Sweden
{marihalldis.tveit}@sweco.se

Kristian Sevdari, Mattia Marinelli, Lisa Calearo
Department of Wind and Energy Systems
Technical University of Denmark
Roskilde, Denmark
{krisse; matm; lica}@dtu.dk

***Abstract*—This paper presents and compares electric vehicle (EV) smart charging (SC) strategies for residential customers with a photovoltaic (PV) system. Three SC strategies are designed with a focus on user interests, the vehicle charges depending on (1) spot price and time-of-use (ToU) tariffs, (2) prognosis for grams of emission per kWh, and (3) own PV production. All strategies consider a local virtual aggregator, which collects information regarding price and emission prognosis, power flow at the household meter, EV connection time, time availability, and EV-user charging needs. Based on a survey of EV Danish owners, three charging patterns are identified and used to compare the effect of varying the charging flexibility within the aforementioned SC strategies. The results show that strategies with regard to price and emission signals are able not only to provide a positive impact on their own specific goal but also to reduce both costs and CO2 emissions. However, this is highly dependent on the connection time of EVs, where overnight charging and more frequent EV connection increase the strategies effect. Charging based on own PV production requires greater user awareness with respect to connection times to have a noticeable effect. However, when the EV is connected during sunny hours, there is good potential for self-consumption increase.**

***Index Terms*—electric vehicle, smart charging, residential flexibility, electricity tariffs, photovoltaic prosumer, CO2 emissions.**

I. Introduction

Denmark has established a stoppage in sales of diesel and oil vehicles by 2030 to reduce CO2 emissions [1]. However, electric vehicles (EVs) can double the average household electricity consumption [2] and the successful implementation of Denmark's goals can put great pressure on the Danish power system [3]. This, together with the expected increase of intermittent renewable sources will create challenges on the power system stability [4]. Such power system challenges seem to be related more to the power delivery, rather than energy terms [5]. In fact, simultaneous charging, especially during peak hours, is a major issue [6]. Uncontrolled charging can easily overload the distribution grid [7]. smart charging (SC) presents a solution where EV becomes a flexible load [8], [9]. The charging flexibility, as defined in [10], can modulate and/or shift the charging power by controlling the current. This can be achieved through centralized, decentralized, or distributed control architectures [11]. This paper considers only one charger, however it is based on the distributed control architecture, as the one that merges decentralized with centralized control for distributed energy resource (DER) coordination [12]. SC strategies are often created with one specific goal, such as: lessen charging costs [8], increase EV owners' rates of renewable power self-consumption [13], reduce load impact [9], [14], or provide ancillary services [10].

This study focuses on flexible residential SC using a virtual aggregator [15], where a distributed autonomous charging control architecture is considered. Three goals of SC are considered: (i) charge during hours with the lowest electricity price, (ii) lower emission footprint and thus lessen the demand for carbon-intensive generating units, or (iii) increase self-consumption by charging during photovoltaic (PV) production and therefore reduce demand from the grid. The first two consider external parameters, that is, electricity price and CO2 emissions, while the last strategy only focuses on the residential system behind the meter. Furthermore, in contrast to other similar studies [8], [14], all SC strategies are tested considering real EV user behavior in terms of plug-in/out times and varying energy demands.

The contributions of this study are as follows:

- Proposal and comparison of SC strategies based on price, self-consumption and C02 emissions.
- Comparison of SC strategies for different user profiles, both in technical and economic terms.
- Guidelines regarding the most suitable strategy for different user connection behaviour.

The remaining of the paper is structured as follows. In Section II the methodology is presented, including the implementation of the model and the charging strategies. Case studies, with the charging patterns of EVs and the characteristics of the residential prosumer, are presented in Section III. The results are discussed in Section IV and the main conclusions are summarized in Section V.

II. Methodology

This section presents the methodology, where the system model is first described in Section II-A and then the three charging strategies are presented in Section II-B.

A. System model

The system accounts for a residential household with a rooftop PV system, and an EV with possibility to be controlled with a virtual aggregator (VA). More information on VA can be found in [15]. The VA retrieves signals of total power flow for the entire system at the metering point, download price and emission prognosis data, while the initial battery level, the energy requested at plug-out time, and EV plug-in/out times are provided from the EV owner.

The entire system is modeled in Matlab Simulink. The base model is divided into four main subsystems that can be viewed in Figure 1. Relevant inputs to the model are the aforementioned signals given to the VA and signals from the charging equipment for EV connection. The system uses a load convention, and thus PV production is negative. The charging control occurs via a proportional integral (PI) controller inside the VA in the charging control subsystem. The input into the PI controller is the total power flow at the smart meter and the desired consumption as a reference. This reference is at the maximum allowed power import at point of common connection (PCC) for the first two strategies or zero when charging to optimize the PV own consumption. A zero as reference means that the smart charger attempts to minimize the import/export exchanges with the grid. Additionally, another step on the control logic, *force charge*, is implemented to ensure the EV reaching its desired battery level before plugging out. The model estimates the battery energy level at each step (each second) of the simulation, and if this dips below the minimum allowed limit, then charging at maximum available power is activated for the remainder of the connection period. To assess the impact of SC, a base dumb charging scenario is considered. Here, EV starts charging at maximum power when plugged in, until the charging goal level is reached.

B. Smart charging strategies

1) Price based: In the first strategy, EV charges according to an electricity price signal. This includes both the spot price based on the day-ahed market and the time-of-use (ToU) tariffs. As spot prices for the following day are published around 13.00 every day [16] and ToU tariffs are established beforehand, each hourly value is known for a maximum of 33 hours forward. When the EV is plugged-in, the necessary charging time is calculated. The hours with cheapest electricity within the connection period are selected to charge the vehicle. From these hours, a threshold is created, and this value is compared with the cost value for each hour during the connected time. If the charge cost is equal to or below this value, the EV will be charged at full capacity, whereas during the remaining time it is idle. The additional logic from the base scenario can be seen in Figure 1 box A).

2) Emission based: This strategy aims to minimize the carbon footprint by charging during periods of lower carbon levels in the grid. The prognosis of the CO2 levels delivered per kWh to the distribution system is based on the day-ahead and intraday market for spot prices, which again predicts the generation mix in the system and the subsequent emissions. However, for this study only the day-ahead market is assumed for the prediction. As actual emission can vary from its prognosis, two methods are considered: 1) charge only during periods of lowest predicted emission levels, and 2) vary charging power according to predicted emission level. The first method is equal to on the price strategy only with emission as a control signal. The latter is a more dynamic charge control, where the charging power varies with the predicted emission level. The charging power depends on the predicted CO2 g/kWh, with only the very lowest amount resulting in the maximum charging power. This method reduces the chance of charging at maximum power for a few hours. The emission control signal is a number between 0 and 1, which is then multiplied with the PI controller output. Positive (1) results in charging at maximum power, while neutral (0) proceeds in no charge. The logic implementation can be seen in Figure 1 box B). For more details on the actual modeling of all strategies, please refer to [2].

3) Self-consumption based: The last strategy is to increase self-consumption, usage of owner PV production, by charging according to the available PV production. Two different methods are designed and compared: 1) charge according to a present threshold of available production surplus, PV production minus house consumption, and 2) charge according to daylight hours. In the first method, PV production is calculated by subtracting the PI controller power output to the vehicle from total power flow at the meter. Two thresholds are investigated, -1 kW and -2 kW. If the available PV power is below (negative due to load convention) these thresholds, the charge is activated. Charging power is decided by the PI controller, while the reference power for PCC is set to zero kW. The charging power is saturated between the maximum and minimum levels of charging current. When there is not enough available PV power, charging is stopped. In the second method, the charging strategy schedules charging for sunny hours during the day. Charging power control is similar to the former method, with the only difference that charging is not stopped within its active period. The logic implementation is shown in Figure 1 box C).

III. Case study

1) EV data: A survey for 14 EV owners residing in Denmark was performed during November and December of 2019 to understand their charging behavior [2]. The information included are: battery size, state-of-charge (SOC) in plug-in and plug-out, plug-in / plug-out times, and charging location, namely: home, work or elsewhere. The charging patterns were classified into three groups of similar behavior with regards to energy demand versus connection time, charging frequency, and battery SOC at plug-in (SOC_{IN}). A representative pattern is chosen from each group and named G1, G2, and G3. These groups represent EV owners with different connection times. In G1, EV owners use the vehicle everyday, and plug-in once arrive at home, independently from battery level, and they do not disconnect until the EV is used again. In G2, EV is connected one / two nights a week, and thus is charged

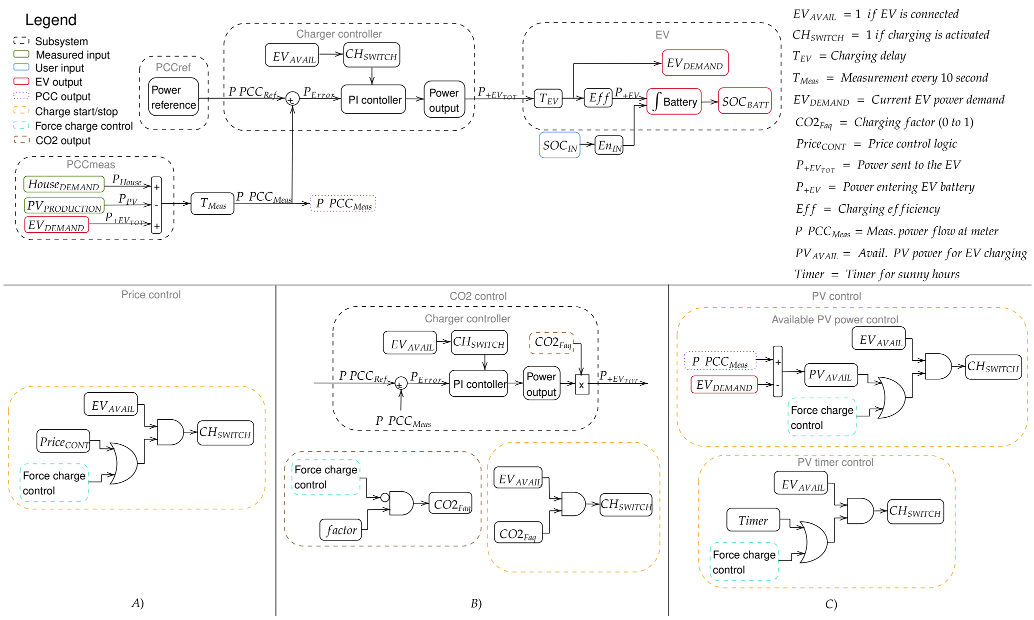


Fig. 1: Simplified schematic overview of the model with charging strategies: self-consumption in A, price in B and emission charging case 2 in C.

less frequently. In this group, users connect and charge their vehicles only if the SOC is below 20 - 30% (value selected from the user). G2 vehicles on average have a higher demand per charging event than G1. Lastly, G3 represents the inflexible group, where vehicles are charged at maximum once a week and connected to the charger only for a limited amount of time. A graphical example of charging times for one arbitrarily week and each representative pattern is provided in Figure 2. For simplicity, the three groups are considered to have the same battery size of 75 kWh and a charging power of 11.1 kW (6-16 A as limiting currents) with 80% charging efficiency at 6A and 90% at 16A. As the case study is for the entire year of 2020, charging connection times are considered to be the same for the 12 months. However, seasonal variations that affect energy consumption are incorporated by varying SOC_{IN} from vehicle efficiency data [17]. More details of the relevant study of EV charging behaviour is given in [2].

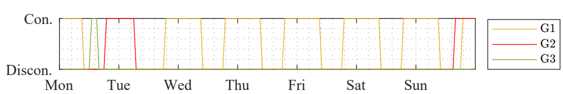


Fig. 2: EV plug-in/ plug-out patterns groups G1 (average distance driven between charging events 80 km), G2 (218 km) and G3 (75 km).

2) System data: Data for household consumption and PV production of a 6 kWp PV plant are taken from a representative household in Denmark for the year 2020. Data are provided with a 5-minute resolution; more details are given in [18]. The hourly spot-prices are retrieved from NordPool [16]. The ToU tariffs are extracted from the largest distribution system operator (DSO) in Denmark, Radius, and its price scheme for residential homes [19]. Emission prognosis data are collected from Energinet [20], [21] for East Denmark grid region (DK2) and have a 5-minute resolution. Sunny hours are defined based on data from the Danmark Meteorologiske Institut [22] and PV production data from the house system with respect to sunrise, sunset and production hours.

The investigated scenarios are summarized in Table I, with names given for each specific scenarios for further reference. Electricity prices broke old records during the year 2021 and therefore represent an interesting case for studying the effect on SC compared to 2020. Therefore, the price-based strategy will be studied with electricity prices from 2021 as a standalone case and analyzed with the original price strategy case in its own subsection. The system layout, production, and consumption data from 2020 are used.

TABLE I: Overview of scenarios including charging pattern groups and charging strategies.

Smart charging	Dumb charging	Electricity price	CO2 low emissions	CO2 varying emissions	PV with threshold	PV with timer
Group 1	G1-Base	G1-Price based	G1-CO2 Case 1	G1-CO2 Case 2	G1-Thr	G1-Timer
Group 2	G2-Base	G2-Price based	G2-CO2 Case 1	G2-CO2 Case 2	G2-Thr	G2-Timer
Group 3	G3-Base	G3-Price based	G3-CO2 Case 1	G3-CO2 Case 2	G3-Thr	G3-Timer

IV. Results

This section presents the results of the SC strategies by comparing the three groups. First, an example of a price-based strategy is given. Then, the annual results are described with a focus on energy consumption, total electricity cost, and CO2 emissions. Finally, to highlight the importance of electricity spot prices, a comparison between the years 2020 and 2021 is considered.

1) Price based: Figure 3 shows the price-based charging strategy for an arbitrary winter week for G1. The upper plot shows household consumption (HC), PV production, export, and import. The charging power and EV SOC are displayed in the middle plot. The lower plot displays the electricity price with the threshold created from the charging strategy. Charging occurs every time the price level is equal to or below the threshold value, and this usually happens during the night. The import of power is clearly higher for EV charging than for other HC loads, indicating the importance of SC for the households total electricity cost. The remaining strategies have similar behavior, but in the following we will only focus on the main results. Annual results are provided in Figure 4, together with emission-based strategies. If focusing on G1- to G3 price based, all groups have a reduction compared to the base case, albeit with varying degrees. G1 has a cost cut of 20% (334 euros), G2 of 10% (63 euros) and G3 of 3% (4 euros).

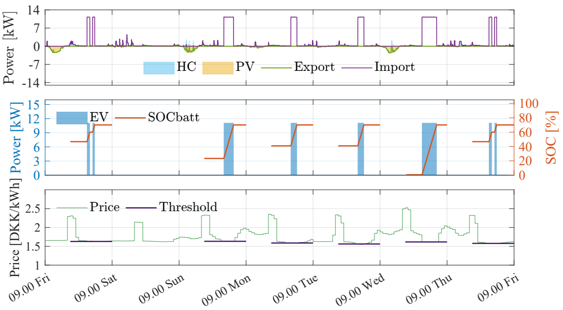


Fig. 3: (upper plot) Power [kW] exchange at the metering point, (middle plot) EV charging (power [kW] and SoC) and (lower plot) electricity price and the price threshold activation for one winter week with G1.

Lowest electricity price in 2020 usually occurred between 02.00-05.00, as it can be observed in Figure 3, indicating the benefit of overnight connection. The comparison between groups hints towards the advantage of more frequent EV connection with lower demand, versus waiting to charge until the battery has a low SOC. G2 has on average double energy demand as G1 per charging event and has half of the cost reduction percentage.

2) Emission based: Total CO_2 g/kWh is analyzed for the base case using both emission strategy methods and compared between groups. However, only EV emissions levels are considered, meaning that the household emissions are disregarded. The main result can be observed in Figure 4 B) with a reduction in total emission from charging for both strategy methods and for all groups. Here, CO_2 case 1 has the highest decrease. This indicates a good correlation between the emission prognosis values and the actual emission levels. The benefit of connecting the vehicle more often is also shown for this strategy. The largest reduction in emissions is G1-CO_2 case 1 and G1-CO_2 case 2 with 21% and 16%, each. G2 has 12% and 3% reductions, and G3 has 6% and 5% reductions in emissions, respectively.

3) Comparison of price and emission based strategies: Figure 4 gives details for the cost of charging with the emission-based strategies and the resulting CO_2 levels after charging according to electricity cost. The results indicate a correlation between low-emission hours and low electricity prices, where the use of a control signal following the prediction of the emission has the ability to reduce the charging cost and vice versa. For the first emission strategy method (CO_2 case 1), all groups have a reduction in cost, the highest being 253 euros for G1. The second case for the emission-based strategy has a smaller decline for all groups. Furthermore, G1-Price based and G2-Price based have a lower total CO_2 level than their CO_2 case 2 scenarios, which further points to the correlation between cost of electricity and CO_2 levels in today's power system.

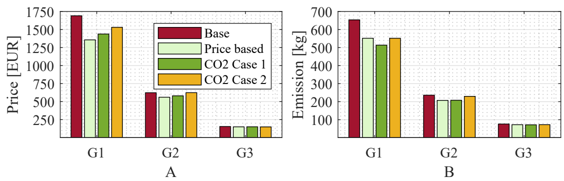


Fig. 4: (A) Cost and (B) emission for one year of charging for all groups when using different smart charging strategies.

4) Self-consumption based: Figure 5 compares the energy used for charging, for all groups in the case of SC with PV self-consumption increase. The share of energy is split between energy from PV entering the EV, PV energy lost, and similar for energy from the grid to the EV. G1 charges every night, therefore it is not possible to utilize the full benefit of the PV system. This group has a modest increase in self-consumption of 125 kWh from the PV system for the most successful case (G1-Thr with -1kW), and only small differences in PV consumption between the subcases. Also, the yearly 125 kWh is negligible compared to the groups total demand of around 6400 kWh, including losses. G2 has greater potential to increase PV consumption, since it is connected more hours during the day. However, the increase in self-consumption is limited, due to other influencing factors, such as the possibility of having cloudy days and the PV consumption is always prioritized first for the household and then for the EV charging. As a result, there is also little difference between any of the methods and dumb charging. In conclusion, we can say that this strategy demands a longer connection time than the minimum charging time. Additionally, a more active behavior is required from the EV owner with connecting the EV when necessary. The third group shows a larger benefit, despite the rare and limited connection periods. The day charging has increased PV utilization from 4.8% to 16.6% for the most successful case (G3-Thr of -1kW). "Thr - 1kW" is the most successful case for all groups with the timer, giving the smallest amount of PV energy to EV.

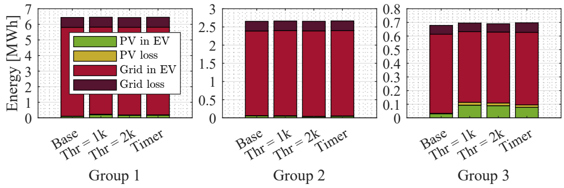


Fig. 5: Charging energy for all groups, coming from PV and grid, and split between the actual energy going to the EV and energy lost during charging.

5) 2020-2021 comparison: For the dumb charging and price based case, the annual costs are compared in Table II by considering both 2020 and 2021 electricity prices. With dumb charging, costs increase by 31%, 36%, and 33% for G1, G2, and G3, respectively. With the price based strategy costs decreased by 25% for G1, 15% for G2 and 5% for G3. In this case also, regular charging yields the highest savings.

TABLE II: Charging costs with price based strategy for 2020 and 2021.

Group	20 Base [€]	20 Cost[€]	21 Base [€]	21 Cost [€]
G1	1692	1358	2219	1670
G2	624	561	849	723
G3	155	150	207	196

V. Conclusion

This paper assesses and compares smart charging strategies with self-consumption, lowering costs and CO2 emissions goals. Each strategy was simulated for a prosumer case with three different real-life charging patterns to gain a wider perspective of the benefit of specific smart charging controls. The most suitable strategy for different user charging behaviors is investigated. For the price based strategy, G1 (EV users that plug-in every night) and G2 (EV users that plug-in once/twice per week overnight) have a noticeable reduction in costs, with a 20% cut for G1. The emission based strategy has a similar maximum drop, 21% for G1 being the largest. The use of price or emission SC strategies reduces both costs and emissions. Most importantly, both strategies point to the benefit of a longer overnight connection and more frequent charging events. The results are opposite for the self-consumption based strategy. There is only a negligible change in the results for vehicles that connect more often and during night. However, a 12% growth could be achieved by connecting the vehicle once a week during daytime hours. This suggests the success of the strategy for consumers who ensure that EV is connected during the day. Lastly, higher electricity costs in 2021 resulted in an increase of 30-35 % in the cost of dumb charging. Price based charging lowered the cost more for 2021 compared to dumb charging than for 2020, with 25% and 20% for G1, group with largest savings. However, in Nordic countries, during a summer day, sunny hours correspond in time with higher electricity prices (for example, during 16:00-20:00), making PV based charging more viable.

Future work on charging designs should focus on revenue from selling excess PV power to the power system, considering weather forecast in self-consumption strategies and introduction of emission taxes as a control signal.

Acknowledgement

The work in this paper is supported by the research project ACDC (EUDP grant nr: 64019-0541) www.acdc-bornholm.eu.

References

[1] S. Jakobsen, L. Flader, P. Andersen, A. Thingvad, and J. Bollerslev, *Sådan skaber Danmark grøn infrastruktur til én million elbiler: Analyse og anbefalinger fra DEA og DTU, november 2019*. Technical University of Denmark, 2020.

[2] M. H. Tveit, "Electric vehicle charging flexibility for behind the meter applications," 2021.

[3] L. Calearo, A. Thingvad, K. Suzuki, and M. Marinelli, "Grid loading due to EV charging profiles based on pseudo-real driving pattern and user behavior," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 3, pp. 683–694, 2019.

[4] J. Østergaard, C. Ziras, H. Bindner, J. Kazempour, M. Marinelli, P. Markussen, S. Rosted, and J. Christensen, "Energy security through demand-side flexibility: The case of denmark," *I E E E Power & Energy Magazine*, vol. 19, no. 2, pp. 46–55, 2021.

[5] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5673–5689, 2013.

[6] J. Bollerslev, P. B. Andersen, T. V. Jensen, M. Marinelli, A. Thingvad, L. Calearo, and T. Weckesser, "Coincidence Factors for Domestic EV Charging from Driving and Plug-in Behavior," *IEEE Transactions on Transportation Electrification*, vol. 7782, no. c, pp. 1–1, 2021.

[7] M. Muratori, "Impact of uncoordinated plug-in electric vehicle charging on residential power demand," *Nature Energy*, vol. 3, no. 3, pp. 193–201, 2018.

[8] E. Sortomme and M. A. El-Sharkawi, "Optimal charging strategies for unidirectional vehicle-to-grid," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 131–138, 2011.

[9] J. A. Lopes, F. J. Soares, and P. M. Almeida, "Integration of electric vehicles in the electric power system," *Proceedings of the IEEE*, vol. 99, pp. 168–183, 1 2011.

[10] K. Sevdari, L. Calearo, P. Bach, and M. Marinelli, "Ancillary services and electric vehicles : an overview from charging clusters and chargers technology perspectives," *Renewable & Sustainable Energy Reviews*, vol. under-review, 2022.

[11] J. García-Villalobos, I. Zamora, J. I. S. Martín, F. J. Asensio, and V. Aperribay, "Plug-in electric vehicles in electric distribution networks: A review of smart charging approaches," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 717–731, 2014.

[12] X. Han, K. Heussen, O. Gehrke, H. W. Bindner, and B. Kroposki, "Taxonomy for evaluation of distributed control strategies for distributed energy resources," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5185–5195, 2017.

[13] L. Calearo, C. Ziras, K. Sevdari, and M. Marinelli, "Comparison of Smart Charging and Battery Energy Storage System for a PV Prosumer with an EV," *IEEE PES ISGT Europe*, 2021.

[14] L. Gan, U. Topcu, and S. H. Low, "Optimal decentralized protocol for electric vehicle charging," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 940–951, 2013.

[15] K. Sevdari, L. Calearo, S. Striani, P. B. Andersen, M. Marinelli, and L. Rønnow, "Autonomously distributed control of electric vehicle chargers for grid services," in *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, pp. 1–5, IEEE, 2021.

[16] "Elspot price data." https://www.nordpoolgroup.com/historical-market-data/.

[17] A. Thingvad, *The Role of Electric Vehicles in Global Power Systems*. PhD thesis, 2021.

[18] C. Ziras, L. Calearo, and M. Marinelli, "The effect of net metering methods on prosumer energy settlements," *Sustainable Energy, Grids and Networks*, vol. 27, p. 100519, 2021.

[19] Radius Elnet A/S, "RADIUS 2021 Tariffs," pp. 1–4, 2021.

[20] "Emission data." https://www.energidataservice.dk/tso-electricity/co2emisprog.

[21] "Declaration emission per hour." https://www.energidataservice.dk/tso-electricity/declarationemissionhour.

[22] D. M. Institut, "Vejrarkiv." https://www.dmi.dk/vejrarkiv/manedens-sasonens-og-arets-vejr/tekst-kort-og-nogletal-maned/.

PAPER [P8]

Flexibility from electric vehicles-residential charging coincidence factors in Norway

Authors:

Aurora Opstad, Kristian Sevdari, Heidi S.Nygård, Bjørn Harald Bakken, Gerard Doorman

Submitted to:

CIGRE PARIS 2024

C1 POWER SYSTEM DEVELOPMENT & ECONOMICS
PS2 - Flexibility as pivotal criterion for system development

Flexibility from electric vehicles - residential charging coincidence factors in Norway

Aurora Opstad
Statnett / Norwegian University of Life Sciences
Norway
aurora.opstad@Statnett.no

Kristian SEVDARI*
Technical University of Denmark -DTU / Statnett
Denmark
krisse@dtu.dk

Heidi S. Nygård
Norwegian University of Life Sciences
Norway
heidi.nygard@nmbu.no

Bjørn Harald Bakken
Statnett
Norway
bjorn.bakken@Statnett.no

Gerard Doorman
Statnett
Norway
gerard.doorman@Statnett.no

* Corresponding author

Keywords: Coincidence factor, Electric vehicles, Residential flexibility, Smart charging

Introduction

The increased penetration of renewable energy sources (RES) and e-mobility can challenge the operation of the electrical power grid [1]. The former challenges the stability of the power system, due to the lack of inertia and intermittency of such weather dependent sources [2]. The latter can be summarized into two main issues, energy, and instantaneous power requirements [3]. While energy needs of e-mobility are not a problem [3], the instantaneous power can become a tall challenge to the power system, in particular in the distribution grid level [3]. Common challenges are grid congestion [4] and voltage stability [5]. However, automation combined with market synchronization can exacerbate such challenges by creating avalanche and rebound effects [3], [4]. Therefore, utilizing demand side flexibility is seen as a valuable solution for the integration of RES and mitigating the challenges from transport electrification [6]. Previous investigations have pointed out the economic and environmental benefits of controlling the electric vehicle (EV) charging process via a "smart charger" in accordance to market signals, system CO2 emissions and local generation [7]. However, the EV charging coincidence factor (CF), due to lack of data, has been barely investigated. CF is the variable that quantifies the availability of the EV fleet for flexibility services. This paper is focused on residential charging which is the dominating form of charging in Norway [3], [8]. Authors of [8] highlight that natural domestic CF is affected by: i) size of the EV fleet considered, ii) pool of EV models and battery size in the EV fleet, iii) charger power, and iv) driving patterns.

This paper further contributes to better understand residential charging CF by presenting the correlations with v) temperature and seasonality, vi) time of the day, vii) day and time of the week. In addition, the investigation presents for the first-time results from smart charging behaviour that is applied in Norway. A comparison between natural (normal) and smart charging behaviour is performed. Here, due to the market synchronization, smart charging impact on power system operation is investigated.

The implications from such investigation are of paramount importance for: i) grid operators to understand future EV charging behaviour, ii) commercial aggregators to better forecast their portfolio consumption, and iii) market players and system operators to better understand the potential of flexibility from residential EV charging.

Methodology

The investigation analyses a data set of 216 households owning a Tesla EV and a smart charger that is remotely controlled to minimize the cost for consumers using an hourly electricity tariff. The data runs from November 2020 to March 2021 and covers customers from all five Norwegian bidding zones that display both dumb (normal) and smart charging behaviour.

Results

Figure 1 compares the CF for smart and normal charging by aggregating all the data in a week and a day. Boxplots are built as a statistical tool to describe the CF distribution on each hour. The results show that smart charging increases the CF in the night hours by shifting the demand to the cheapest electricity hours. In addition, weekdays have higher CF than weekends.

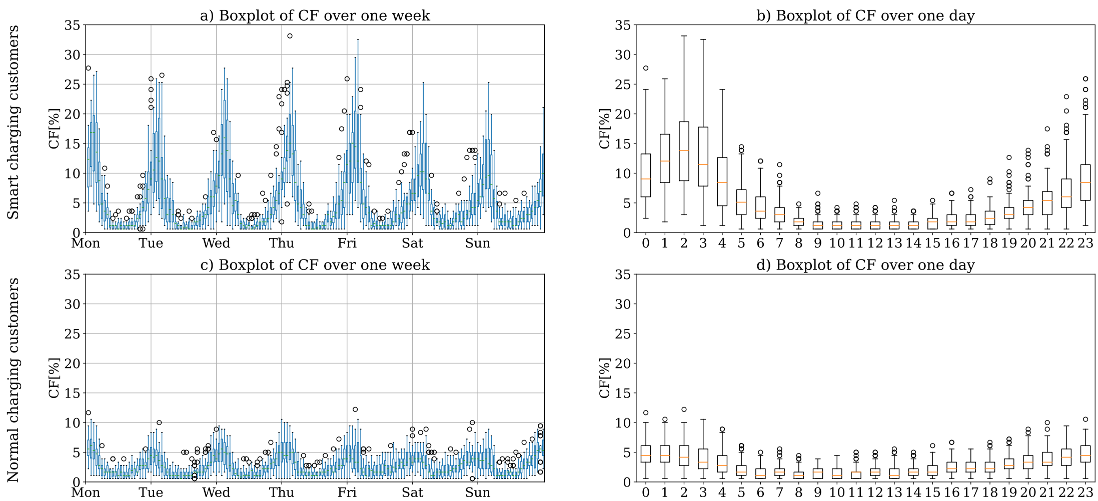


Figure 1. Boxplot of coincidence factor for: smart charging customers aggregated in a week a) and a day b), normal charging customer aggregated in a week c) and a day d).

The full paper will further contribute to the quantification of residential CF based on the Norwegian dataset. Such quantification will consider temperature and seasonality, electricity price and bidding zones, and aggregated hourly and weekly behavior. Lastly, the full paper will discuss possible implications from market synchronization and solutions to better design smart charging packages for end users.

References

[1] B. Mohandes, M. S. El Moursi, N. Hatziargyriou, and S. El Khatib, “A Review of Power System Flexibility with High Penetration of Renewables,” *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 3140–3155, 2019, doi: 10.1109/TPWRS.2019.2897727.

[2] F. Milano, F. Dorfler, G. Hug, D. J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems (Invited Paper),” *20th Power Syst. Comput. Conf. PSCC 2018*, pp. 1–25, 2018, doi: 10.23919/PSCC.2018.8450880.

[3] K. Sevdari, L. Calearo, P. B. Andersen, and M. Marinelli, “Ancillary services and electric vehicles: An overview from charging clusters and chargers technology perspectives,” *Renew. Sustain. Energy Rev.*, vol. 167, no. April, p. 112666, 2022, doi: 10.1016/j.rser.2022.112666.

[4] T. Unterluggauer, F. Hipolito, S. Klyapovskiy, and P. B. Andersen, “Impact of Electric Vehicle Charging Synchronization on the Urban Medium Voltage Power Distribution Network of Frederiksberg,” *World Electr. Veh. J.*, vol. 13, no. 10, pp. 1–18, 2022, doi: 10.3390/wevj13100182.

[5] M. Neaimeh *et al.*, “A probabilistic approach to combining smart meter and electric vehicle charging data to investigate distribution network impacts,” *Appl. Energy*, vol. 157, pp. 688–698, 2015, doi: 10.1016/j.apenergy.2015.01.144.

[6] M. Z. Degefa, I. B. Sperstad, and H. Sæle, “Comprehensive classifications and characterizations of power system flexibility resources,” *Electr. Power Syst. Res.*, vol. 194, no. February, p. 107022, 2021, doi: 10.1016/j.epsr.2021.107022.

[7] M. H. Tveit, K. Sevdari, M. Marinelli, and L. Calearo, “Behind-the-Meter Residential Electric Vehicle Smart Charging Strategies: Danish Cases,” *2022 Int. Conf. Renew. Energies Smart Technol. REST 2022*, 2022, doi: 10.1109/REST54687.2022.10022910.

[8] J. Bollerslev *et al.*, “Coincidence Factors for Domestic EV Charging from Driving and Plug-In Behavior,” *IEEE Trans. Transp. Electrif.*, vol. 8, no. 1, pp. 808–819, 2022, doi: 10.1109/TTE.2021.3088275.

Department of Wind and Energy Systems
Division for Power and Energy Systems
Technical University of Denmark
Frederiksborgvej 399
DTU Risø Campus, 4000 Roskilde
Denmark

https://windenergy.dtu.dk/english
Tel: (+45) 46 77 50 85
E-mail: communication@windenergy.dtu.dk